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FINAL SUMMARY TECHNICAL REPORT

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FRACTURE CHARACTERISTICS OF STRUCTURAL METALS

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MATERIALS PROCESSING DEPARTMENT
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STRUCTURAL METALS

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Submitted By:

G. L. Hanna
E. A. Steigerwald

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Materials Research & Development
TAPCO - a division of
Thompson Ramo Wooldridge Inc.
23555 Euclid Avenue
Cleveland 17, Ohio

FOREWORD

This Final Summary Report is submitted by the Materials Research and Development Department, TAPCO - a division of Thompson Ramo Wooldridge Inc., in accordance with the provisions of Contract No. N 600(19) 58831. The work was administered under the direction of the Bureau of Naval Weapons, Navy Department, with Mr. George M. Yoder, as project engineer.

This report describes the results of the program during the period 1 July, 1962 to 1 July, 1963 and was:

Prepared By: G. L. Hanna

G. L. Hanna, Metallurgist

E. A. Steigerwald

E. A. Steigerwald, Research Supervisor

Approved By: G. J. Guarnieri

G. J. Guarnieri, Department Manager

ABSTRACT

An experimental program was conducted to determine the plane strain fracture toughness (K_{IC}) of the following high-strength materials:

1. 4340 steel (two strength levels),
2. H-11 steel (four strength levels),
3. Maraging steel (two strength levels) and,
4. Beta titanium (one strength level).

The K_{IC} parameter was determined from circumferentially precracked round specimens and by resistance measurements conducted on precracked sheet specimens. Several heats of each material were evaluated over temperatures ranging from -100°F to 300°F.

Although specific problems occurred in the maraging steel evaluations, the overall results indicated that reasonably good consistency existed between heats of sheet material. The experimentally determined data were combined with results of plane strain fracture toughness presented in the literature to produce typical room temperature K_{IC} values for 4340 and H-11 sheet which could be considered for inclusion in MIL Handbook 5.

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I INTRODUCTION

Catastrophic failure of components at stress levels below their design values has often been experienced, particularly with very high-strength materials. These brittle failures usually bear no relation to the conventional smooth strength or ductility of the material, however, they can be directly correlated to some parameter which evaluates relative notch sensitivity. Although a designer can obtain the tensile and yield strength of a material as handbook data, no fracture parameter is currently available in handbook form which will quantitatively rate prospective constructional metals in terms of their resistance to crack propagation. A serious problem results with the employment of a parameter such as notch tensile strength to rate material reliability in the presence of severe stress concentrators, since the nominal failure stress of a structure or a test specimen with a sharp notch is dependent on geometrical considerations and is not an intrinsic property of the material.

The development of fracture mechanics has introduced the concept that the stress environment at the tip of the crack determines the point at which rapid crack extension occurs. This technique which has been described and verified in the literature (1, 2)* employs a material parameter called fracture toughness (K_{IC}) to characterize the stress intensity at the crack tip when catastrophic failure occurs. The determination of fracture toughness as a material evaluation parameter has many advantages since it eliminates the influence of specimen width and crack size in the evaluation model and provides some measure of the strength characterisitcs of full-size components. The propagation of a crack, however, in sheet material generally consists of a normal and shear mode. The shear mode which occurs at the free surface represents a high energy component of crack growth while the normal, plane strain mode which is present at the specimen center provides a low energy contribution. As the specimen thickness is progressively increased, the contribution of the shear lips becomes a lower percentage of the total energy for crack propagation. As a result, the fracture toughness (K_{IC}) which is related to the energy necessary for crack propagation decreases as the specimen thickness increases. At large thicknesses the fracture toughness approaches a constant value which represents the plane strain fracture toughness (K_{IC}).

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* Numbers in parentheses pertain to references in the Bibliography.

Since plane strain fracture toughness is, in principle, completely independent of specimen dimensions it represents a convenient handbook parameter to characterize the load-carrying ability of high-strength materials in the presence of crack-like defects. This material parameter (K_{IC}) is of basic importance. It is not only capable of predicting the total failure of very thick components but it also defines the stress level at which slow crack growth is initiated in relatively thin sections (3, 4). Recent studies on actual pressure vessels have indicated the suitability of the fracture mechanics approach towards predicting component failure, from relatively simple laboratory tests on precracked specimens (5, 6).

In addition, the plane strain fracture toughness appears to represent a basic material parameter which can be related to a variety of fracture parameters, and which can be used to characterize other failure mechanisms (e.g. low-cycle fatigue) (6).

The purpose of this program is to study the possibility of employing the plane strain fracture toughness (K_{IC}) as a handbook parameter to evaluate the fracture characterisitcs of high-strength metals (strength-to-density ratios greater than 7.5×10^5 in.). Such a parameter, if suitable, would be presented to the MIL Handbook 5 committee for possible incorporation into handbook form.

The present program involved the following three phases:

1. A literature survey to determine if the previously published notch data would yield suitable K_{IC} values.

2. The evaluation of high-strength materials in a test program to obtain K_{IC} values that would supplement existing data.

3. Suitable compilation of the test data for presentation to the ANC-5 Handbook committee.

II LITERATURE SURVEY

A survey of the published data on the notch properties of high-strength-to-weight materials was conducted to determine the relative quantity of useable information that could be employed to evaluate plane strain fracture toughness. In practice the plane strain fracture toughness (K_{IC}) has been determined from at least five different test methods:

a) Tensile tests on circumferentially-notched round specimens,

b) Measurement of the stress to initiate slow crack growth in a sheet tensile specimen,

c) Tensile test with a surface-cracked sheet specimen,

d) Notched bend test (slow or impact strain rates),

e) Tensile test on single edge-notched specimen.

In all test methods the presence of a precrack is generally considered a necessary condition for the accurate determination of fracture toughness (7). The actual methods which are used to calculate K_{IC} from the various test techniques are summarized in Table 1. A large amount of the published data concerning notch tests do not conform to the requirements for accurate K_{IC} measurements. In many cases the use of precracking was not employed, and/or the section size was not sufficiently large so that the failure stress was significantly greater than the yield strength.

In the literature survey, data obtained from specimens with notch radii less than 0.0015" have been included. In all cases the results are presented in a form so that the precracked specimens which do not violate the condition for accurate plane strain fracture toughness measurements can be readily distinguished from the data which cannot be used for quantitative parameter determinations.

The results of the literature survey are presented in Tables 2 through 12. In determining K_{IC} from sheet tests, only the data obtained from actual measurements of the initiation of slow crack propagation obtained from either compliance gauges, resistance measurements, or acoustic pick-ups, were used.

In the survey, the materials are classified in terms of the following categories:

1. Low alloy martensitic steels (Tables 2 to 9)
2. Hot-work die steels (Table 10)
3. Special high-strength steels (Table 11)
4. Aluminum and titanium (Table 12)

The analyses of the materials covered in the literature survey are presented in Table 13.

1. Low Alloy Martensitic Steels

In addition to the tabular representation, selected data are also given in graphical form. Figure 1 indicates the standard method of presentation. The smooth strength and the plane strain fracture toughness (K_{IC}), which is the selected crack propagation parameter, are plotted as a function of tempering temperature. Although the individual data points are indexed in the tables, the figures merely show a composite of all data in order to give a qualitative indication of the relative scatter in the particular evaluation parameters. Data for 4340 steel, obtained on circumferentially-notched specimens, oriented in the longitudinal direction and tested at room temperature are presented in Figure 1. Several interesting points are apparent with reference to the K_{IC} parameter. In cases where machined notches were used and where $\sigma_N > 1.1\ F_{TY}$*, the values of plane strain fracture toughness were higher than when $\sigma_N < 1.1\ F_{TY}$. The use of a machined notch would be expected to raise the "apparent" K_{IC} due to the blunt notch effect, while the precracked specimens with $\sigma_N > 1.1\ F_{TY}$ would exhibit measured K_{IC} values below the true parameter. In cases where machine notches are present and $\sigma_N >$ 1.1 F_{TY}, it is not always obvious as to what factor will predominate. In the data obtained in the survey precracked specimens produced a significantly lower value of K_{IC} than the machine-notched specimens at the lower tempering temperatures, and were the only results that could be considered as valid measurements of K_{IC}.

Data for specimens of 4340 steel oriented in the transverse direction are presented in Figure 2. In this case, all the results were obtained on circumferentially machine-notched specimens.

The influence of test temperature on the K_{IC} parameter is presented in Figure 3. A decrease in test temperature significantly decreased the apparent plane strain fracture toughness. It is also interesting to note that the K_{IC} values obtained in the lower temperature tests indicated the region of irreversible "500°F embrittlement" which occurs in the 4340 steels, while the K_{IC} parameters obtained from the room temperature tests were not sufficiently sensitive to detect this embrittlement with the particular specimen geometries employed.

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* σ_N = net notch tensile strength; F_{TY} = 0.2% yield strength.

The results obtained on the modified 4330 steel (AMS 6434) are presented in Figure 4. The K_{IC} values, which were obtained from several sources, showed a relatively large degree of scatter. The K_{IC} results for this lower carbon steel were higher than the 4340 steel. The fracture parameters for a 4330 steel, modified with silicon and vanadium, are presented in Figure 5. The K_{IC} values were generally obtained under conditions where $\sigma_N > 1.1\ F_{TY}$, and therefore probably are not representative of the true parameter. In addition, these values were obtained by one investigator, and are indicative of only one heat of material.

The smooth tensile and fracture toughness results obtained for the 300M high-strength steel tested in the longitudinal direction are given in Figure 6. Although only limited data are available, the precracked specimens produced K_{IC} values which were considerably lower than those obtained with machined notches. Data for 300M, tested in the transverse direction, are presented in Table 8 while results obtained on a variety of low alloy martensitic high-strength steels are summarized in Table 9. In general, precracking was not employed, and the K_{IC} values were obtained on specimens where σ_N was greater than 1.1 F_{TY}.

2. Hot-Work Die Steel

The results obtained with the hot-work die steels are presented in Table 10 and Figure 7. Much of the K_{IC} data were obtained on precracked specimens and the rapid rise in K_{IC} over the 1000 to 1100°F tempering temperature interval is certainly noteworthy.

3. Special High-Strength Steels

Only a limited amount of plane strain fracture toughness data have been published on the special types of high-strength steels. These results are presented in Table 11 for AM 355, 17-7PH, and the maraging steel.

4. Aluminum and Titanium Alloys

The data on aluminum and titanium alloys are presented in Table 12. The results were obtained with both round and sheet specimens, and both machined notches and precracked specimens were used.

5. Summary of Literature Survey

The major portion of published data on the notch properties of high-strength steels have been obtained under conditions which do not allow valid calculations of plane strain fracture toughness. In general, the application of fracture mechanics to testing and the adoption of specimen precracking as a method of generating a sharp notch are relatively new techniques. As a result, the currently published data do not readily provide a large amount of information which can be directly integrated into handbook form. At present, however, the fracture mechanics approach to the evaluation of high-strength materials is being widely used and, as a result, a large quantity of useful fracture toughness data should be available in the near future. It is encouraging to note that the limited data which are published on precracked specimens indicate a reasonably good agreement between investigators.

III EXPERIMENTAL PROGRAM

An experimental program was initiated to provide a necessary supplement to the existing K_{IC} data and to evaluate the suitability of employing this parameter in MIL Handbook 5. The general approach employed in the program was to test several heats of the selected materials over a range of test temperatures.

1. Materials

The following four materials were chosen for the experimental program:

a) 4340 steel (air melt),

b) H-11 die steel (vacuum melt),

c) 18% nickel maraging steel (vacuum melt),

d) Beta titanium.

A summary of the material variables is presented in Table 14.

The 4340 steel was selected as representative of a widely-used, air-melted, low alloy martensitic high-strength steel, and should serve as a convenient reference for discussing the significance of the K_{IC} parameter for design purposes. The H-11 die steel was chosen as a tool steel which is presently included, along with 4340, in MIL Handbook 5. The 18% nickel maraging steels are representative of a new class of ultra high-strength materials which depend on an aging reaction, rather than carbon, to develop the high-strength properties. The beta titanium was selected as a high-strength, non-ferrous material. Both the beta titanium and the 18% nickel maraging steel represent materials which are being considered for future inclusion in MIL Handbook 5.

The 4340 and H-11 steels were austenitized in neutral salt baths and tempered in an air furnace. After heat treatment, 0.006 to 0.008" of stock was removed from each side of the sheet material to eliminate any possible effects due to decarburization.

The maraging steels were austenitized and aged in an air furnace. Testing was performed on the as-received stock with no surface removal. The beta titanium was received from the vendor in the solution treated condition and aged for 72 hours at 900°F in a vacuum chamber (approximately 1 micron). Subsequent to heat treatment the titanium was pickled in an aqueous solution of 3% HF and 30% HNO_3 to remove approximately 0.002" of material from each surface.

2. Test Techniques

The general scope of the experimental program involved selecting several high-strength constructional metals and determining the significant strength parameters (i.e. F_{TU}, F_{TY}, and K_{IC}) for these materials. The geometries of the smooth and notched sheet tensile specimens used in this investigation are shown in Figures 8 and 9. In the sheet materials the plane strain fracture toughness K_{IC} was determined from resistance measurements on the center-notched, precracked specimens. This technique which has been previously described involves making the specimen one leg of a Kelvin-Wheatstone double bridge and measuring the increase in resistance which accompanies the crack extension (3). The method is capable of detecting crack extensions of the order of 0.003". Typical load-resistance curves are shown in Figures 10A and B. The point where slow crack growth is initiated corresponds to the load at which the curve deviates from linearity (Figure 10A). Under certain conditions this deviation corresponds to a noticeable discontinuity in the measuring parameter (pop-in) (Figure 10B). Since the initiation of slow crack growth generally occurs under plane strain conditions, the conventional Irwin formula (2) can be used to calculate the stress intensity parameter at this point to yield the value of plane strain fracture toughness. The test method generally produces results which are analogous to those obtained by the more conventional displacement gage techniques (30). It should be noted that in many high-strength steels a noticeable "pop-in" is not observed when slow crack growth is initiated. As has been previously discussed, this lack of an observable "pop-in" is not a unique function of the test method but is dependent on the particular material (3). The presence of a "pop-in" is apparently not a necessary condition since reliable plane strain fracture toughness values have been obtained by using the approach based on the deviation from linearity (3, 4). Previous work on aluminum (4) has also indicated that a "pop-in" occurs when the plastic zone is less than about one-fourth the specimen thickness. In addition, reliable K_{IC} data were obtained when the plastic zone size was less than one-half the thickness. In many tests with high-strength steels a "pop-in" does not occur despite the fact that the plastic zone size is considerably less than one-fourth the thickness and additional work is still required to define the conditions under which measureable "pop-in" can be observed in this class of materials.

In bar stock, the K_{IC} parameter was determined from circumferentially precracked specimens. The geometry of the round specimens is presented in Figure 11. An axial alignment fixture (32) which insured an eccentricity less than 0.001" was used for the notch tests on round specimens, which had a notch strength less than approximately 200,000 psi.

The apparatus for precracking round specimens is illustrated in Figure 12. The cracks were produced by mounting one end of the specimen, containing a machined notch with a 0.005" radius, in the chuck of a lathe. A bending moment was applied to the end of the specimen with a smooth-surfaced knurling tool and the resulting deflection was measured on a dial gage. As the crack progressed, the load-carrying area of the specimen decreased and an increased deflection was indicated on the dial gage. This technique consistently produced concentric cracks between 0.005" and 0.010" in depth.

The testing sequence involved conducting tests at -100, -45, 40, 75, 200 and 300°F at a crosshead speed of 0.010 in/min. for the notch specimens and at a strain rate of 0.010 in/in/min. for the smooth specimens. Two replicas per variable were used in the smooth tests and three specimens per variable in the notch tests. The low-temperature tests were conducted in a special apparatus which employed liquid nitrogen vapor. The apparatus was similar to that developed by Wessel and Olleman (33). With the use of an automatic controller and solenoid, that governed the flow of nitrogen vapor, the temperature variation during a test was less than ±2°F. A diagram of the low-temperature test facility is presented in Figure 13. Tests above room temperature were conducted in conventional resistance-heated furnaces.

3. Results and Discussion

a. 4340 Steel, 400°F T per

The smooth tensile properties of three heats of 4340 steel, tempered at 400°F are presented in Figure 14. The reproducibility between heats was excellent and the properties conformed to previously published data (18).

The notched tensile strengths* of the 4340 steels are shown in Figure 15 as a function of test temperature. A comparison between the sheet materials (heat 7C-8236 and 7C-8657) indicates that significant differences occurred in notch properties. Due to the increased constraint present in the round specimens, the notch strength was consistently higher with this type of specimen geometry. The notch tensile strength did not continually rise with increasing test temperature but reached a maximum at approximately 100°F. This decrease in notch properties at higher test temperatures has been previously studied and is caused by a strain aging effect which occurs in this type of high-strength steel (34). These results also indicate that K_{IC} at the higher temperatures would be strain rate dependent.

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* The notch tensile strength is defined as the maximum load divided by the initial cross-sectional area of the specimen in the plane of the notch.

The plane strain fracture toughness K_{IC}* for the 4340 steels (see Figure 16) exhibited an overall trend that was comparable to the notch tensile strength. The decrease in K_{IC} with decreasing temperature, however, was not as abrupt as that shown by notch strength parameters. In the sheet material, heat 7C-8236 had K_{IC} values which were slightly higher than heat 7C-8657. Both sheet materials had K_{IC} values which were significantly less than those present in the bar stock.

b. <u>4340 Steel, 750°F Temper</u>

The smooth tensile properties of the three heats of 4340 steel tempered at 750°F are presented in Figure 17. The smooth properties were extremely reproducible and showed virtually no variation as a function of heat. Both the tensile and yield strength exhibited a mild increase with decreasing test temperature.

The notch tensile properties, shown in Figure 18, indicated that heat 7C-8657 had slightly lower properties than heat 7C-8236. Specimens from this heat also started to undergo a transition in the -45 to -100°F range.

The plain strain fracture toughness of the 4340 steel tempered at 750°F was very sensitive to the particular heat (see Figure 19). The K_{IC} values for the round bars were significantly higher than the sheet specimens over the entire test temperature range. In the circumferentially precracked specimens at this strength level the notch tensile strength was generally greater than 1.1 times the yield strength. On this basis the reported K_{IC} values may actually be lower than the true K_{IC} which could be obtained with larger specimens. Despite this fact the measured K_{IC} data obtained from the bar stock were still higher than that present in the sheet material.

c. <u>H-11 Steel</u>

The properties of the hot-work die steel were evaluated at four strength levels in material obtained from two heats (one sheet, one bar). The smooth tensile properties of the steel tempered at 1000, 1050, 1100, and 1150°F are presented in Figures 20 to 23. For each of the tempering treatments the smooth tensile strength of the bar stock was slightly higher than the sheet material. This effect was more predominant at the lower tempering temperatures.

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* Example calculations illustrating the method in which K_{IC} was determined from the test data are shown in Appendix I.

The notch tensile properties of both the sheet and bar stock of H-11 steel as a function of test temperature are shown in Figures 24 through 27. All the sheet materials exhibited transitions from brittle to ductile fracture in the range of test temperatures evaluated. Using 100% shear as the criterion for the transition behavior in sheet material, the transition temperatures progressively decreased from 300°F for the specimens with the 1000°F temper to approximately -75°F for the samples tempered at 1150°F.

The plane strain fracture toughness of the H-11 steel is summarized in Figures 28 through 31. The K_{IC} values for specimens tempered at 1000 and 1050°F exhibited steadily increasing fracture toughness with increasing test temperature. At the lower strength levels (higher tempering temperatures), the net notch strength in the round specimens exceeded the yield strength in certain cases and the measured fracture toughness was therefore lower than the true parameter. This is shown in Figure 30 and 31 by arrows attached to the data points obtained from specimens tested at the higher test temperatures. For sheet specimens of H-11 tempered at 1100 and 1150°F and tested above room temperature, the plastic zone size (r_p) was larger than one-half the thickness. This condition may have accounted for the fact that the measured K_{IC} value tended to reach limiting values between 90,000 psi $\sqrt{\text{in.}}$ and 100,000 psi $\sqrt{\text{in.}}$ for the steel tempered at 1100 and 1150°F. This point must be resolved by additional tests using thicker specimens.

The transverse smooth and notch properties of the H-11 sheet were evaluated in room-temperature tests. In general, for this material, the properties in the transverse direction were only slightly below those obtained in the longitudinal direction.

d. Maraging Steel (18% Ni, 7% Co, 5% Mo)

The maraging steel designated as 250,000 psi yield strength material was evaluated in sheet and bar form after annealing at 1500°F and aging for three hours at 900°F. The smooth strength properties are presented as a function of test temperature in Figure 32. At a given temperature the bar stock had strength properties which were approximately 25,000 psi higher than the sheet material. This difference could be attributed to the slightly higher titanium and carbon content present in the bar stock heat.

As shown in Figure 33, the notch tensile properties, of the sheet material showed considerably different behavior as a function of test temperature than the bar stock. The notch tensile strength of the sheet steel decreased slightly as the test temperature was increased while the bar stock markedly increased with increasing test temperature and exhibited a much higher degree of scatter.

An interesting effect was noted during the determination of plane strain fracture toughness in the maraging steels. A typical load-resistance curve is presented in Figure 34. The conventional method of determining K_{IC} is indicated in the figure where the load (Point A) at which a significant deviation from linearity occurs is employed to calculate K_{IC}. Upon closer examination of a large number of load-resistance curves, a very slight deviation can be observed at a much lower value of applied load, (Point B). The question arises as to what degree of slow crack extension is actually taking place in the region A-B and what significance does this have in the determination of K_{IC} for design purposes. In an effort to answer these questions a specimen was loaded, as indicated in Figure 34, in the region where only a slight deviation from linearity occurred. It was then unloaded, heat tinted, and pulled to failure. As shown in Figure 35, a very slight amount of crack extension (less than 0.010") actually accompanied the slight deviation from linearity which was present in the load-resistance curve.

In Figure 36, two values of the plane strain fracture toughness for the 250,000 psi grade of maraging steel are presented. The lower value corresponds to the load at which the first slow crack growth is detected (Point B), while the second value is indicative of a marked acceleration in slow crack extension and approximates the plane strain fracture toughness which would be obtained by conventional displacement gage techniques (Point A). At present the significance of these widely different K_{IC} values in design applications is not known. The scatter in the lower values of K_{IC} was considerably greater than the higher values due to the difficulty in determining when the very small increment of crack growth had actually occurred.

The rapid decrease in the "high value" of K_{IC} which occurred in the 18% nickel, 7% cobalt maraging steel between -45 and -100°F does not conform with previously obtained data (35, 36) and is not the normally expected temperature dependence for K_{IC}. This behavior may be indicative of the fact that the "high value" of K_{IC} is not really the true K_{IC} value and contains some contribution due to the shear lip. In addition, the calculated plastic zone size for the "high" K_{IC} value is considerably larger than one-half the specimen thickness and on this basis it also represents a doubtful K_{IC} value (4, 36).

K_{IC} values obtained from the bar stock were significantly lower than the sheet material at the low test temperatures and markedly increased with increasing test temperature. The maraging steels represented the only group of materials where the bar stock exhibited properties as a function of test temperature which were qualitatively different from the sheet.

e. Maraging Steel (18% Ni, 9% Co, 5% Mo)

The smooth and notch tensile properties of the higher strength, 9% cobalt, maraging steel in sheet form are presented in Figure 37. The smooth strength exhibited the same trend, as a function of test temperature, that was observed for the 18-7-5 steel. Both heats exhibited similar smooth properties over the entire range of test temperatures. The net notch strength of both heats decreased slightly with increasing test temperatures.

The plane strain fracture toughness for both heats are shown in Figure 38. In this 9% cobalt maraging steel, as in the case of the 7% cobalt grade, the phenomenon of very slight crack growth occurred relatively early in the test and two values of K_{IC}, calculated on the basis of the first indication of crack growth and the rapid extension of the slow crack growth, are included in Figure 38. The "higher" K_{IC} values showed no consistent trend as a function of test temperatures between 300 and -45°F. At the -100°F test temperature a noticeable decrease occurred. The "lower" K_{IC} values indicated that heat W-24178 had a slightly inferior fracture toughness which increased slightly with increasing test temperature. The "lower" K_{IC} values for heat 06498 were relatively insensitive to test temperature.

f. Beta Titanium

The smooth strength properties of three heats of beta titanium aged 72 hours at 900°F are presented in Figure 39. The results indicate that a rather wide variation in strength properties occurred between heat F7798 (sheet) and heats F7769 (sheet) and F6997 (bar). The smooth strength decreased rather consistently as a function of increasing test temperature and this strength decrease was attended by a slight increase in tensile ductility.

The notch tensile properties of the beta titanium are shown in Figure 40. A transition in fracture appearance occurred in the sheet material at approximately 200°F. The notch tensile strength steadily increased with increasing test temperatures. The plane strain fracture toughness for the beta titanium is presented in Figure 41 as a function of test temperature. At temperatures below approximately 100°F both heats of sheet material had comparable plane strain fracture toughnesses, however at higher temperatures the lower strength heat had slightly greater K_{IC} values. A comparison between the two heats with comparable yield strengths (heat 7769 sheet and heat 6977 bar) indicated that at all test temperatures the bar stock had K_{IC} values which were approximately 5000 psi$\sqrt{\text{in.}}$ greater than those obtained with sheet specimens from heat 7769.

g. Summary of Experimental Program

All the test data for the four classes of materials are summarized in Tables 15 through 35. In general, a noticeable difference in K_{IC} values existed between heats of materials, particularly the test results between bar stock and sheet, and on this basis the fracture toughness data were not sufficient to allow them to be combined to determine statistical averages or variances. The plane strain fracture toughness obtained at the higher strength levels and lower test temperatures appeared to be more consistent and conformed to expected behavior. The tests conducted with the maraging steel in sheet form were particularly difficult to interpret due to a very slight amount of slow crack growth which occurred at a relatively low load.

Despite the fact that in certain cases apparent anomalies occurred, the data agreed reasonably well with previously published work. In addition obvious differences were apparent between the fracture toughness of various materials heat treated to comparable strength levels. This point is illustrated in Figure 42 where the test data for various materials are compared.

IV APPLICATION OF DATA TO HANDBOOK PRESENTATION

At present a serious need exists to provide the designer with a material parameter which can be used to predict the reliability of a material in structural applications, just as tensile and yield strengths are used to predict the maximum or useful load-carrying capacity. In general, many of the parameters, such as notch tensile strength, which are used to characterize reliability or relative susceptibility to brittle fracture are not material constants. At present plane strain fracture toughness (K_{IC}) represents the only single-valued parameter which can be simply employed in a handbook to provide an indication of crack propagation resistance. Although there are specific criticisms which can still be directed against the use of K_{IC}, the fact remains that it can be determined from simple laboratory tests and used both qualitatively and quantitatively as an aid in the solution of material selection problems.

For a number of years both metallurgists and designers have qualitatively employed relative rating parameters such as notch tensile strength ratio, transition temperature, or impact energy to provide some indication of regions where dangerous embrittlements may exist. These parameters clearly establish the irreversible temper embrittlement which occurs in low alloy martensitic steels when they are tempered in the 500°F to 600°F range. In many cases, however, it is difficult to compare, even qualitatively, notch strength ratios obtained on different materials because much of the available data has been determined from specimens with varying notch geometries. The use of a standardized parameter such as K_{IC} which is a material constant will allow a continuous assembly of unambiguous data to be obtained and will simplify the qualitative evaluation of various materials and heat treatments.

The real advantage of the plane strain fracture toughness parameter as an evaluation tool rests in its ability to provide a quantitative prediction of the load-carrying capacity of a structure. To illustrate this point a pressure vessel made of H-11 steel will be considered. The properties of the H-11 steel as obtained from MIL Handbook 5 are presented in the following table along with the K_{IC} parameters obtained from tests on sheet specimens.

PROPERTIES OF 5 Cr-Mo-V AIRCRAFT STEEL (H-11)

Alloy	5 Cr-Mo-V
Form	All wrought forms
Condition	Heat treated (quenched and tempered) to obtain F_{TU} indicated

Mechanical Properties:

F_{TU}, ksi L	240	260	280
F_{TY}, ksi L	200	220	240
K_{IC}, ksi $\sqrt{\text{in.}}$ L	73	46	32

For the basis of this illustration, consider the flaw as a partial surface crack and assume that the nondestructive testing technique is capable of detecting cracks greater than 0.050" in depth. This implies that cracks 0.050" or less may be present in the completed structure. For a partial surface crack, the plane strain toughness can be expressed as:

$$K_{IC}^2 = \frac{3.77\,\sigma^2 b}{\phi^2 - .212\,\dfrac{\sigma^2}{\sigma_{ys}^2}} \qquad (4)$$

where: K_{IC} is the plane strain fracture toughness;

σ is the gross applied stress;

a is length of surface crack;

b is depth of surface crack;

σ_{ys} is 0.2% offset yield strength; and

ϕ is an elliptic integral defined as

$$\phi = \int_0^{\pi/2} \left(1 - \left(\frac{a^2 - b^2}{a^2}\right) \sin^2\theta\right)^{\frac{1}{2}} d\theta$$

For reliable performance the applied stress (σ) should be equal to the yield strength (σ_{ys}). For the H-11 steel with a 220,000 psi yield strength and an (a/b) ratio of 2, the calculations indicate that the K_{IC} value should be greater than approximately 64,000 psi $\sqrt{\text{in.}}$ to insure that the defect does not grow and lead to failure below the design stress. Since the actual K_{IC} value for this strength level in the 5 Cr-Mo-V is 46,000 psi $\sqrt{\text{in.}}$, the designer would select a material with a higher fracture toughness or decrease the applied stress level. This quantitative approach to predicting the stresses where flaws start to grow as cracks can be applied to virtually any component provided that adequate stress analyses are available to define the relationship between the material constant K_{IC} and the crack geometry.

The use of K_{IC} as a quantitative design number is actually a conservative criterion, since it predicts the onset of slow crack growth and not complete structural failure. In many cases, slow crack growth may be significant and failure will occur at higher values of applied stress than predicted from K_{IC} data. The inclusion of K_c which characterizes final failure along with K_{IC} in handbook form however, is difficult since the K_c value is not a true material constant, but varies with thickness.

Although some question still remains concerning the variability of K_{IC} as a function of heat of steel, sufficient data currently exist for certain steels in sheet form to allow values to be considered for handbook presentation. In addition, K_{IC} data are being obtained from a variety of steels and test methods in a large number of current test programs. It is anticipated that the results of these programs can be readily integrated into the format of MIL Handbook 5 once the basic pattern of presentation is resolved.

The Tables 36 and 37 indicate the suggested format for presenting K_{IC} in MIL Handbook 5 for the alloy steels and for the 5 Cr-Mo-V Aircraft Steel. A summary of the valid K_{IC} data for sheet materials of these two steels is presented in Figures 43 and 44. The data for the low alloy steels has been obtained only on a 4340 steel and this fact should be noted in the handbook. The K_{IC} values presented in Tables 36 and 37 have been selected from Figures 43 and 44 to conform to the strength levels listed in the handbook. In the case of 4340 at the 176,000 psi yield level a questionable extrapolation has been used, this, however, is not a serious drawback since reliability and notch sensitivity are not considered serious problems at this low strength level.

A compilation of this type will allow the designer to integrate into his material selection a parameter which measures the relative ability of a material to perform reliably in the presence of severe stress concentrations. Although it would certainly be desirable to have available a considerably larger quantity of data to establish typical K_{IC} values, the current information on sheet material is reasonably consistent to allow typical room temperature values to be reported for certain steels. It is not believed advisable at this time to report in handbook form K_{IC} values for 4340 and H-11 as a function of test temperatures above room temperature. In the case of 4340 a strain aging type of embrittlement occurs which produces K_{IC} values which are dependent on strain rate. In the case of H-11 steel, at the lower strength levels, the K_{IC} data above room temperature may not be valid due to the formation of extensive plastic zones at the crack tip.

Once the K_{IC} concept is accepted for handbook presentation it can be periodically expanded:

1) To provide statistical parameters,

2) To include other materials, such as the precipitation-hardening stainless steels, titanium and aluminum, and

3) To include values over a wider range of temperatures.

V SUMMARY AND CONCLUSIONS

An investigation was conducted to determine the feasibility of employing plane strain fracture toughness (K_{IC}) as a handbook design parameter to rate the ability of a material to resist brittle crack propagation. A literature survey indicated that a large portion of the published data was obtained prior to the adoption of formal fracture mechanics testing techniques. As a result, only a realtively small quantity of valid K_{IC} data were available. To supplement the existing data an experimental program was conducted to determine the plane strain fracture toughness of four materials:

1) 4340 steel (two strength levels, three heats),
2) H-11 steel (four strength levels, two heats),
3) Maraging steel (two strength levels, four heats),
4) Beta titanium (one strength level, three heats).

Tests were conducted over a range of test temperatures from -100°F to 300°F with both circumferentially-precracked, round tensile specimens and center-cracked sheet specimens. The results were sufficiently consistent so that typical room temperature K_{IC} values could be obtained on sheet material of 4340 and H-11 steel and presented for possible inclusion in MIL Handbook 5. Certain problems existed in determining K_{IC} from sheet specimens of the maraging steel due to a very small amount of slow crack growth which occurred at relatively low loads. Additional tests must be conducted to determine the correlation of this small degree of growth with K_{IC} values determined by other methods.

Despite the fact that specific questions exist concerning the proper methods of determining K_{IC} and the correlation between different test techniques, the concept of applying K_{IC} as both a qualitative and quantitative handbook value appears valid. Current data indicate that significant differences in K_{IC} do exist between materials and as such it represents a useful qualitative parameter which can also be employed to provide a quantitative measure of component reliability.

VI APPENDIX

1. Determination of K_{IC} Parameter from Sheet Specimens

Since the initiation of slow crack growth is generally governed by plane strain conditions, the load at which crack growth starts can be used to determine the plane strain fracture toughness from tests on sheet specimens. The governing equation is:

$$K_{IC}^2 = \sigma_{gi}^2 W \tan \left(\frac{\pi a}{W} + \frac{K_{IC}^2}{2W\sigma_y^2} \right) \qquad (1)$$

where:

K_{IC}	=	plane strain fracture toughness
a	=	one-half the initial crack length
W	=	specimen width
σ_{gi}	=	gross section stress at which slow crack growth is initiated
σ_y	=	yield strength

This equation can be solved graphically for K_{IC} (Reference 2, Figure 4) from a knowledge of the specimen dimensions, the yield strength of the material and the load at which slow crack growth is initiated.

2. Methods Used to Determine K_{IC} from Circumferentially-Precracked Specimens

The K_{IC} values can be computed from circumferentially-precracked round specimens by employing the method used by Carmen, Armiento and Markus (9):

$$K_{IC} \left[1 - \frac{K_{IC}^2}{2\pi \sigma_y^2 D} \right]^2 = 0.233 \sigma_n \sqrt{\pi D} \qquad (2)$$

where:

K_{IC} = plane strain fracture toughness

σ_y = 0.2% yield strength

d = specimen diameter at the base of the notch

σ_n = net notch tensile strength

D = major specimen diameter

This equation, which applies when the ratio d/D is equal to 0.707, can be rewritten in the form:

$$X \left[1-1/2\, X^2\right]^2 = 0.233 \frac{\sigma_n}{\sigma_y} \qquad (3)$$

where:

$$X = \frac{K_{IC}}{\sigma_y} \frac{1}{\sqrt{\pi D}} \qquad (4)$$

Equation 3 is presented in graphical form in Figure 45. Plane strain fracture toughness can be determined from this figure from a knowledge of the σ_n/σ_y ratio.

In actual experimental practice it is difficult to accurately control the precrack to produce exact d/D values of 0.707. Variations from this ideal d/D ratio were taken into account by applying the corrections factors described by Wundt (36). These corrections factors are plotted as a function of d/D in Figure 46. In practice the K_{IC} values calculated from equation 4 and Figure 45 were multiplied by the appropriate correction factor given in Figure 46 to produce the reported values of plane strain fracture toughness.

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TABLE 1

Test Techniques Used to Calculate K_{IC}

Test Method	Conditions for Accurate Measurement of K_{IC}	Method of Calculating * K_{IC}
Tensile Test on Precracked Round Specimen	$\sigma_N < 1.1\ F_{TY}$	$K_{IC} = 0.414\ \sigma_N \sqrt{D}$ (formula applies for notch specimens where $d/D = 0.707$)
Tensile Test on Center Notch, Precracked Sheet Specimen	$\sigma_{ig} < 0.8\ F_{TY}$ $r_p < 2t$	$K_{IC} = \sigma_{ig} \left[W \tan \frac{\pi a_o}{W} \right]^{1/2}$
Tensile Test on Edge Notch, Precracked Sheet Specimen	$\sigma_{ig} < 0.8\ F_{TY}$ $r_p < 2t$	$K_{IC} = \sigma_{ig} \left[W \tan \frac{\pi a_o}{W} + 0.1 \sin \frac{2\pi a_o}{W} \right]^{1/2}$
Tensile Test on Surface-Cracked Specimen	$\sigma_f < F_{TY}$	$K_{IC}^2 = \frac{3.77\sigma^2 b}{\phi^2 - .212\left(\frac{\sigma}{F_{TY}}\right)^2}$
Single Notch Specimen	$\sigma_f < F_{TY}$	Experimental Calibration
Bend Test Brittle Boundary Test	} Not Included In Literature Survey	

* All K_{IC} values are corrected for plasticity by adding a plastic zone size $r_p = \frac{K_{IC}^2}{2\pi\sigma_y^2}$

σ_N = Net Notch Tensile Strength

σ_{ig} = Gross stress at which slow crack growth is initiated

W = Specimen Width

$2a_o$ = Initial Crack Size

σ = Gross Failure Stress

F_{TY} = 0.2% Yield Strength

b = Crack Depth

ϕ = Elliptic Integral

t = Thickness

Table 2 ER-5426

Mechanical Properties of 4340 Steel, Longitudinal Direction, Room Temperature Tests, Specimens Austenitized 1550°F to 1600°F, Oil Quenched, Tempered 1 Hour, As Indicated (Notch Radius less than 0.0015")

	Strength (1000 psi)			K_{IC}	Spec.	Spec.Dia.+		
Temper	Ultimate	0.2% Yield	Notch**	Ksi√in	Type	Or Width-in.	Ref.	Comments
350	300	--	340	77.1			15	
400	285	--	310	70.3	Rd	0.300	17	
400	275	230	275	86.3	Rd	0.500	18	
400	275	230	300	78.2	Rd	0.300	18	
400	270	--	335	76.0	Rd	0.300	18	
400	275			32.1	Rd	0.750	13	Precracked Spec.
400	275			30.0	Rd	0.750	13	" "
400*	250			32.5	Rd	0.540	13	" "
400*	250			32.4	Rd	0.540	13	" "
400	275	218	280	89.9	Rd	0.500	20	
400	275		330	74.9	Rd	0.300	15	
400	275		250	73.2	Rd	0.500	15	
400	265		275	80.5	Rd	0.300	15	
400	280		190	55.6	Rd	0.500	15	10" Sect. Size
400	270	225	310	79.8	Rd	0.300	18	
400	300	225	275	68.9	Rd	0.300	18	
400		235		41.4	Single Notch		24	Precracked Spec.
500	265	225	300	76.5	Rd	0.300	18	
500	265		312	86.5	Rd	0.300	18	
500	260	225	280	70.0	Rd	0.300	18	
500	260		285	71.1	Rd	0.300	18	
500	270		310	80.2	Rd	0.300	18	
500	265		302	68.5	Rd	0.300	17	
500	265		335	76.0	Rd	0.300	18	
500	260		330	74.9	Rd	0.300	15	
500	265		315	71.5	Rd	0.300	18	
500	270		190	48.3	Rd	0.500	15	10" Sect. Size
600	250		314	71.2	Rd	0.300	15	
600	250		302	68.5	Rd	0.300	17	
600	240		330	68.1	Rd	0.300	15	
600	245	225	310	70.3	Rd	0.300	18	
600	242	228	280	88.4	Rd	0.300	17	
600	250		225	74.7	Rd	0.500	15	
600	250		290	84.9	Rd	0.300	15	
600	250		165	48.3	Rd	0.500	15	10" Sect. Size
600	240	225	305	77.6	Rd	0.300	18	
600	250		310	85.5	Rd	0.300	18	
600		220		52.1	Single Notch		24	Precracked Spec.
700	235	220	305	78.1	Rd	0.300	18	
700	225	220	300	75.9	Rd	0.300	18	
700	225		280	81.6	Rd	0.500	15	
700	225		298	67.6	Rd	0.300	17	
700	235	220	270	85.2	Rd	0.500	18	
700	235	220	310	78.0	Rd	0.300	18	
700	225		305	69.2	Rd	0.300	18	
700	225		298	67.6	Rd	0.300	17	
700		210		65.5	Single Notch		24	Precracked Spec.
800	215	200	295	79.7	Rd	0.300	18	
800	210	200	300	80.5	Rd	0.300	18	
800	200		290	84.9	Rd	0.300	15	
800	220		220	64.4	Rd	0.500	15	10" Sect. Size
800	210		300	68.1	Rd	0.300	17	
800	215	210	275	87.9	Rd	0.500	18	
800	215	210	290	73.5	Rd	0.300	18	
800	210		300	68.1	Rd	0.300	15	

* 2 Hour Temper

** Notch strength is σ_{gi} (see Table 1) for sheet spec. or σ_N for round specimens.

\+ Major specimen diameter.

Table 3

Mechanical Properties of 4340 Steel, Transverse Direction, Room Temperature Tests

Specimens Austenitized 1550°F to 1600°F, Oil Quenched, Tempered 1 Hour As Indicated

(Machined Notch Radius less than 0.0015")

Temper	Strength (1000 psi) Ultimate	Strength (1000 psi) 0.2% Yield	Strength (1000 psi) Notch	K_{IC} Ksi√in	Spec. Type	Spec. Dia. Or Width-in.	Ref.
400	275	230	255	60.4	Rd	0.300	18
400	300		210	50.3	Rd	0.300	18
400	275	220	215	66.0	Rd	0.500	18
400	275	220	270	66.3	Rd	0.300	18
400	275		280	69.5	Rd	0.300	18
500	275	235	260	61.7	Rd	0.300	18
500	260		205	49.2	Rd	0.300	18
500	260	235	250	58.2	Rd	0.300	18
500	265	235	250	58.2	Rd	0.300	18
600	240	230	265	64.2	Rd	0.300	18
600	250		210	50.3	Rd	0.300	18
600	240	225	245	58.0	Rd	0.300	18
600	240	225	275	70.0	Rd	0.300	13
700	235	215	195	60.5	Rd	0.500	17 & 18
700	235	215	265	64.8	Rd	0.300	17 & 18
700	230	220	265	67.1	Rd	0.300	18
700	235		210	50.3	Rd	0.300	18
700	225		270	68.4	Rd	0.300	18
800	220	205	230	69.2	Rd	0.500	20
800	220	205	280	70.7	Rd	0.300	18
800	210		220	54.7	Rd	0.300	18
800	210		300	68.1	Rd	0.300	15

Table 4

Mechanical Properties of 4340 Steel, Longitudinal Direction, Subzero Temperature Tests, Specimens Austenitized 1550°F to 1600°F, Oil Quenched, Temper 1 Hour As Indicated, (Machined Notch Radius less than 0.0015")

Temper	Strength (1000 psi) Ultimate	Notch	K_{IC} Ksi√in	Test Temperature	Spec. Type	Spec. Dia. (in.)	Ref.
400	305	290	65.8	-100	Rd	0.300	17
400	340	220	49.9	-320	Rd	0.300	17
500	285	245	55.6	-100	Rd	0.300	17
500	275	240	54.5	-100	Rd	0.300	17
500	315	140	31.8	-320	Rd	0.300	17
600	270	280	63.5	-100	Rd	0.300	17
600	298	125	28.4	-320	Rd	0.300	17
700	250	280	63.5	-100	Rd	0.300	17
700	285	195	44.3	-320	Rd	0.300	17
800	215*	285	64.7	-100	Rd	0.300	17
800	202*	280	63.5	-100	Rd	0.300	17
800	220*	152	34.5	-320	Rd	0.300	17
800	270	202	45.8	-320	Rd	0.300	17

* Room Temperature Tensile Strength

Table 5

Mechanical Properties of Mod. 4330, (ASM 6434), Room Temperature Tests

(Machined Notch Radius less than 0.0015")

Temper	Direction	Strength 1000 psi Ultimate	0.2% Yield	Notch	K_{IC} Ksi $\sqrt{in}$	Specimen Type	Spec. Dia. Or Width-in.	Ref.
400	Long.	250	200	330	83.6	Round	0.300	18
400	Long.	260	225		62.2	Sheet	3.0	12
400	Long.	260	221		112.5	Sheet	3.0	20
500	Long.	240	190	300	108.1	Round	0.500	18
625	Long.	225	190	285	79.4	Round	0.300	18
625	Long.	225	190	280	95.0	Round	0.500	18
700	Long.	215	206		136.0	Sheet	3.0	11
700	Long.	215	205		90.5	Sheet	3.0	11
700	Long.	215	202		124.0	Sheet	3.0	11
800	Long.	205	194		126.0	Sheet	3.0	11
800	Long.	205	190		108.0	Sheet	3.0	11
800	Long.	205	194		117.0	Sheet	3.0	11
400	Trans.	260	221		94.9	Sheet	3.0	11
400	Trans.	250	200	255	65.1	Round	0.300	18
400	Trans.	250	200	220	68.0	Round	0.500	18
500	Trans.	240	190	210	65.3	Round	0.500	18
625	Trans.	220	190	245	60.9	Round	0.300	18
625	Trans.	220	190	200	59.4	Round	0.500	18
700	Trans.	215	206		118.0	Sheet	3.0	11
700	Trans.	215	205		83.5	Sheet	3.0	11
700	Trans.	215	202		112.5	Sheet	3.0	11

Table 6

Mechanical Properties of 4330 (Mod + Si) Steel, Room Temperature Tests

Longitudinal Direction

(Notch Radius less than 0.0015")

Temper	Strength (1000 psi) Tensile	0.2% Yield	Notch	K_{IC} Ksi√in	Specimen Type	Spec. Dia. or Width-in.	Ref.	Comments
350	279	181	245	79.8	Round	0.505	8	
450	270	207	279	91.3	Round	0.505	8	
450	270	207	241	90.8	Round	0.750	8	
450	275	220	270	83.2	Round	0.505	9	
450	269	203	266	87.0	Round	0.505	8	
550	266	216	240	74.8	Round	0.505	8	
550	266	216	245	76.2	Round	0.505	8	
550	266	216	243	87.2	Round	0.750	8	
550	266	216	240	86.1	Round	0.750	8	
600	262	207	255	80.9	Round	0.505	8	
600	262	207	229	71.7	Round	0.505	8	
600	262	207	251	95.6	Round	0.750	8	
600	262	207	270	89.2	Round	0.505	19	
600	262	207	231	88.8	Round	0.750	19	
600	262	207	237	91.8	Round	0.750	19	
600	262	207	196	94.3	Round	1.25	19	
600	262	207	107	76.3	Round	3.00	19	Slack-quenched Structure
650	259	209	236	73.7	Round	0.505	8	
650	259	209	274	89.5	Round	0.505	8	
650	259	209	223	83.7	Round	0.750	8	
650	259	209	228	85.3	Round	0.750	8	
750	238	189	208	64.3	Round	0.505	8	
750	238	189	200	60.7	Round	0.505	8	
750	238	189	201	74.2	Round	0.750	8	
750	238	189	187	69.8	Round	0.750	8	
850	232	175	212	66.2	Round	0.505	8 & 19	
850	232	175	190	58.4	Round	0.505	8 & 19	
850	232	175	178	67.4	Round	0.750	8 & 19	
850	232	175	182	68.7	Round	0.750	8 & 19	

Table 7

Mechanical Properties of 300M Steel, Room Temperature Tests, Longitudinal Direction

(Notch Radius less than 0.0015")

Temper	Strength (1000 psi) Tensile	0.2% Yield	Notch	K_{IC} Ksi√in	Spec. Type	Spec.Dia. Or Width-in.	Ref.	Comments
400	301	218	233	71.4	Round	0.505	8	
400	301	218	233	71.4	Round	0.505	8	
400	295	215	312	85.5	Round	0.300	18	
400	290	215	79	52.3	Sheet	1.750	3	Precracked Spec.
500	285	225	73	48.5	Sheet	1.750	3	Precracked Spec.
600	275	225	315	79.8	Round	0.300	18	
600	275	225	275	87.2	Round	0.500	18	
600	285	235	237	73.5	Round	0.505	8	
600	285	235	255	78.0	Round	0.505	8	
600	280	232	253	77.5	Round	0.505	8	
600	280	232	258	78.9	Round	0.505	8	
600	280	230	73	50.0	Sheet	1.750	3	Precracked Spec.
700	275	230	312	77.0	Round	0.300	18	
700			72	49.0	Sheet	1.750	3	Precracked Spec.
750	270	217	226	70.5	Round	0.505	8	
750	270	217	216	67.0	Round	0.505	8	
800			62	41.1	Sheet	1.750	3	Precracked Spec.
800			70	46.5	Sheet	1.750	3	Precracked Spec.
850	250	210	199	60.3	Round	0.500	8	
850	250	210	201	60.9	Round	0.500	8	
850	240		187	55.0	Round	0.500	16	
850	240		216	63.5	Round	0.500	16	
850	250	210		77.8	Round		10	
850	248	211		32.1	Sheet	1.0	12	Elliptical Crack

Table 8

Mechanical Properties of 300M Steel, Room Temperature Tests, Transverse Direction

(Notch Radius less than 0.0015")

Temper	Strength (1000 psi) Tensile	0.2% Yield	Notch	K_{IC} Ksi√in	Spec. Type	Spec. Dia. Or Width-in.	Ref.	Comments
400	295	225	280	68.0	Round	0.300	18	
400		231	34.2	41.1	Sheet	1.750	3	Precracked Spec.
400		231	35.9		Sheet	1.750	3	Precracked Spec.
500		229	35.9	45.4	Sheet	1.750	3	Precracked Spec.
500		229	35.4	40.5	Sheet	1.750	3	Precracked Spec.
600	275	225	325	80.9	Round	0.300	18	
600	275	225	245	75.9	Round	0.500	18	
600			37.7	43.2	Sheet	1.750	3	Precracked Spec.
700			25.7	31.3	Sheet	1.750	3	Precracked Spec.
700			25.0	28.6	Sheet	1.750	3	Precracked Spec.
800			26.7	30.8	Sheet	1.750	3	Precracked Spec.
800			26.3	30.1	Sheet	1.750	3	Precracked Spec.

Table 9

Mechanical Properties of Various Low Alloy Martensitic Steels, Room Temperature Tests,

(Machined Notch Radius Less Than 0.0015", Round Specimens)

Steel	Temper °F	Direction	Strength (1000 psi) Tensile	Strength (1000 psi) 0.2% Yield	Notch	K_{IC} Ksi$\sqrt{in}$	Spec. Major Dia. - in.	Ref.	Comments
2340	400	Long	285		315	71.5	0.300	15	
2340	450	Long	270		210	61.5	0.500	21	
2340	450	Long	270		240	70.3	0.500	21	
2340	550	Long	250		175	56.7	0.300	15	
2340	600	Long	230		315	71.5	0.300	15	
2340	650	Long	220		265	77.6	0.300	15	
2340	650	Long	220		280	81.2	0.300	15	
5140	350	Long	280		173	50.7	0.500	15	
5140	400	Long	270		175	51.3	0.500	21	
5140	400	Long	275		238	54.0	0.300	15	
5140	550	Long	235		287	65.1	0.300	15	
5140	650	Long	220		225	65.9	0.500	21	
5140	650	Long	220		220	64.5	0.500	15	
3140	400	Long	270		180	52.7	0.500	15	
3140	400	Long	273	233	173	49.5	0.500	23	
3140	550	Long	241	216	183	56.7	0.500	23	
3140	550	Long	240		170	58.6	0.500	15	
3140	550	Trans	237		200	49.8	0.500	15	
1340	400	Long	280		200	45.4	0.300	15	
1340	400	Long	285		200	58.6	0.500	15	
1340	450	Long	270		120	35.2	0.500	21	
1340	550	Long	250		110	45.4	0.300	15	
1340	600	Long	230		255	74.6	0.500	15	
1340	600	Long	230		230	52.2	0.300	15	
1340	650	Long	220		200	58.6	0.500	21	
98B40	600	Long	280	245	200	61.2	0.500	18	
98B40	600	Long	280	245	280	67.2	0.300	18	
98B40	600	Trans.	280	245	240	57.2	0.300	18	
98B40	600	Trans.	280	245	145	42.9	0.500	18	
98B40	650	Long	248	225	220	67.5	0.500	18	
98B40	650	Long	248	225	229	53.6	0.300	18	
98B40	650	Trans.	245	225	235	54.7	0.300	18	
98B40	650	Trans.	245	225	160	49.2	0.500	18	

Table 9 (Cont'd)

Steel	Temper °F	Direction	Strength (1000 psi) Tensile	Strength (1000 psi) 0.2% Yield	Notch	K_{IC} Ksi$\sqrt{in}$	Spec. Major Dia. - in.	Ref.	Comments
Super.Hy.Tuf.		Long	260	205	175	53.5	0.500	18	
Super.Hy.Tuf.		Trans.	260	220	230	53.5	0.300	18	
Super.Hy.Tuf.		Trans.	240	205	165	38.9	0.300	18	
Super.Hy.Tuf.		Trans.	240	205	100	30.8	0.500	18	
X-200	450	Long	300	240	210	79.0	0.750	10	
X-200	450	Long	300	240	225	68.5	0.505	10	
X-200	550	Long	290	250	200	74.0	0.750	10	
X-200	550	Long	290	250	200	65.0	0.505	10	
X-200	650	Long	285	245	200	62.0	0.505	10	
X-200	650	Long	285	245	190	70.0	0.750	10	
X-200	700	Long	275	225		59.1	1.0	12	Sheet ellip. crack
X-200	700	Long	275	240	170	52.0	0.505	10	
X-200	700	Long	275	240	145	52.0	0.750	10	
X-200	750	Long	270	225	205	62.0	0.505	10	
X-200	750	Long	270	225	150	55.0	0.750	10	
X-200	850	Long	260	195	225	69.0	0.505	10	
X-200	850	Long	260	195	175	66.0	0.750	10	
X-200	950	Long	240	210	250	80.0	0.505	10	
X-200	950	Long	240	210	215	80.0	0.750	10	
X-200	700	Long	290	240		49.3	Sheet spec.1.0"	12	-100°F ellip.crack
X-200	700	Long	295	250		38.9	Sheet spec.1.0"	12	-150°F ellip.crack
X-200	700	Long	310	263		36.1	Sheet spec.1.0"	12	-200°F ellip.crack
D-6 AC	300	Long	335	202	190	60.0	0.505	10	
D-6 AC	400	Long	315	240	205	63.0	0.505	10	
D-6 AC	500	Long	280	250	190	59.0	0.505	10	
D-6 AC	600	Long	280	250	225	70.0	0.505	10	
D-6 AC	700	Long	270	245	225	69.0	0.505	10	
D-6 AC	800	Long	250	225	225	72.0	0.505	10	
D-6 AC	900	Long	235	220	270	85.0	0.505	10	
D-6 AC	900	Long				73.0	Surface cracked spec.	25	Variety of surface crack dimensions
D-6 AC	400	Long				52.6	Surface cracked	25	" " "
D-6 AC		Long	218	195		108	Precracked round	35	$\sigma_N < \sigma_Y$

Table 10

Mechanical Properties of H-11 Steel, Room Temperature Tests

Longitudinal Direction

(Notch Radius Less than 0.0015")

Temper	Strength (1000 psi) Tensile	0.2% Yield	Notch	K_{IC} Ksi$\sqrt{in.}$	Spec. Type	Spec. Dia. Or Width-in.	Ref.	Comments
900			60	40.0	Sheet	1.75	3	Precracked
1000			60	40.0	Sheet	1.75	3	Precracked
1050			80	62.0	Sheet	1.75	3	Precracked
1050		232		59.2	Sheet	1.0	12	Elliptical Crack
1050		232		41.2	Sheet	1.0	12	Elliptical Crack
1075		225	45	38.0	Sheet	3.0	26	Precracked
1075	246	200	254	82.5	Round	0.505	13	
1075	246	199	254	82.7	Round	0.505	8	
1075	244	197	210	63.3	Round	0.505	8	
1075	244	197	229	70.7	Round	0.505	8	
1075	244	197	229	70.7	Round	0.505	8	
1075	244	197	211	63.3	Round	0.505	8	
1075	244	197	230	70.7	Round	0.505	8	
1100		190	160	135.5	Sheet	1.75	3	Precracked
1075	245			49.2	Sheet	1.0	12	Precracked -110°F
1075	245			37.6	Sheet	1.0	12	Precracked -110°F
1075	282			26.7	Sheet	1.0	12	Precracked -280°F
1075	282			22.9	Sheet	1.0	12	Precracked -280°F

Table 11

Mechanical Properties of Special High-Strength Steels, Room Temperature Tests, Longitudinal Direction (Notch Radius Less Than 0.0015")

Steel	Temper	Strength (1000 psi) Tensile	0.2% Yield	Notch	K_{IC} Ksi $\sqrt{in}$	Spec. Type	Spec. Dia. Or Width-in.	Ref.	Comments
AM 355	SCT 850			70.0	58.0	Sheet	1.75	3	Precracked
AM 355	SCT 850			68.0	56.0	Sheet	1.75	3	Precracked
AM 355	SCT 1000			70.0	58.0	Sheet	1.75	3	Precracked
17-7PH	RH 950	220		78.0	58.0	Sheet	1.75	3	Precracked
17-7PH	RH 1000	220		70.0	58.0	Sheet	1.75	3	Precracked
17-7PH	RH 1050	212		70.0	60.0	Sheet	1.75	3	Precracked
17-7PH	RH 1100	190		73.0	65.0	Sheet	1.75	3	Precracked
17-7PH			168		49.0	Sheet		28	Surface-cracked
17-7PH			162		53.2	Sheet		28	Surface-cracked
18% Ni Maraging	900°F	250	240	186.0	188.0	Sheet	1.75	3	Precracked
18% Ni Maraging	900°F		290		78.0	Sheet	0.75	25	Surface-cracked Several crack sizes.
18% Ni Maraging	900°F		260		86.0	Sheet		27	Precracked

Table 12

Mechanical Properties of Aluminum and Titanium Alloys, Room Temperature Tests

Longitudinal Direction (Notch Radius less than 0.0015")

Material	Strength (1000 psi) Tensile	0.2% Yield	Notch	K_{IC} Ksi$\sqrt{in}$	Spec. Type	Spec. Dia. or Width-in.	Ref.	Comments
Al 6061 T-6		40		71.5	Round		1	
Al 2024 T-4		45		69.2	Round		1	
Al 7075 T-6		72		36.8	Round		1	
Al 7075 T-6		72		31.5	Round		1	
Al 7075 T-6		72		31.5	Sheet		1	
Al 7075 T-6				35.5	Single-edge notch		29	Precracked Spec.
Ti 6Al-4V	205		195	40.4	Round	0.250		
Ti 6Al-4V	185		230	52.2	Round	0.300	16	Test Temp.-100°F
Ti 6Al-4V	162		220	49.9	Round	0.300	16	Room Temp.
Ti 6Al-4V	135		192	43.6	Round	0.300	16	Test Temp. 300°F
Ti 6Al-4V	125		178	40.4	Round	0.300	16	Test Temp. 500°F
Ti 6Al-4V	126		185	41.8	Round	0.300	16	Test Temp. 700°F
Ti 6Al-4V	118		175	39.7	Round	0.300	16	Test Temp. 800°F
Ti 6Al-4V	163.5			71.8	Sheet	3.0	11	Acoustic Tests Room Temp.
Ti 6Al-4V		167		39.0	Forging	1.0	25	Surface-Cracked
Ti 6Al-4V		152		44.6	Forging	1.0	25	Surface-Cracked
Ti 6Al-4V		147		52.2	Plate	1.0	25	Surface-Cracked
Ti 155A	220		110	24.6	Round	0.300	16	
Ti 155A	220		121	27.5	Round	0.300	16	
B 120 VCA	172			46.0	Sheet	3.0	11	Acoustic Tests

Table 13

Compositions of Materials Evaluated

Material	C	Mn	Si	Ni	Cr	Mo	V	Al	P	S	Other
4340 Nominal	.38-.43	.60-.80	.20-.35	1.65-2.00	.70-.90	.20-.30	-	-	.040 max.	.040 max.	
Ref. 18 Heat 1	.41	.79	.31	1.83	.77	.23	-	-	.013	.016	
Heat 2	.40	.74	.19	1.83	.77	.24	-	-	.023	.029	
Heat 3	.42	.83	.30	1.77	.80	.24	.07	-	.014	.013	
Heat 4	.41	.75	.31	1.76	.81	.24	-	-	.011	.014	
Ref. 17	.39	.76	.29	1.84	.72	.23	-	-	.015	.015	
4330V (Mod + Si)											
Ref. 8, 9, 10	.34	.98	1.37	1.82	.95	.42	.14	-	.015	.005	
(Mod) Ref. 18	.32	.88	.26	1.79	.84	.36	-	-	.012	.018	
1340 Nominal	.38-.43	1.60-1.90	.20-.35	-	-	-	-	-	.040 max.	.040 max.	
2340 Nominal	.38-.43	.70-.90	.20-.35	3.25-3.75	-	-	-	-	.040 max.	.040 max.	
3140 Nominal	.38-.43	.70-.90	.20-.35	1.10-1.40	.55-.75	-	-	-	.040 max.	.040 max.	
Ref. 23	.40	.76	.26	1.37	.66	-	-	-	.020	.015	
5140 Nominal	.38-.43	.70-.90	.20-.35	-	.70-.90	-	-	-	.040 max.	.040 max.	
98B 40											
Ref. 18	.46	.79	.35	.86	.81	.19	-	-	.017	.017	
X-200	.43	.89	1.53	.10	2.05	.52	.07	-	.013	.015	.09 Cu
300M											
Ref. 18 (Tricent)	.39	.74	1.54	1.83	.83	.38	.07	-	.014	.014	
D-6 AC Nominal	.46	.75	.22	.55	1.00	1.00	-	-	-	-	
H-11 Nominal	.40	.25	.10	-	5.00	1.30	.50	-	-	-	

Table 13 (Cont'd)

Material	C	Mn	Si	Ni	Cr	Mo	V	Al	P	S	Other
Hy-Tuf Ref. 18	.28	1.29	1.58	1.87	.24	.40	.17	-	.019	.015	
Super Hy-Tuf Ref. 18	.41	1.28	1.77	-	1.26	.33	-	-	.014	.024	
18% Ni-Co-Mo Maraging Steel-Nominal	.02	.10 max.	.10 max.	18.0	-	5.0	-	.10	.01 max.	.01 max	7.0 Co
AM 355 Stainless Nominal	.14	.75	.30	4.25	15.5	2.75	-	-	.04 max.	.03 max.	.10 N
17-7 PH Stainless (Nominal)	.07 max.	.50	.50	7.00	17.00	-	-	1.20	.04 max.	.04 max.	
Al 2024 Nominal	Al Alloy; Nominal Comp. 3.8-4.9 Cu; 1.2 -1.8 Mg										
Al 7075 Nominal	Al Alloy; Nominal Comp. 5.1-6.1 Zn; 2.1-2.9 Mg; 1.2-2.0 Cu; .18-.40 Cr										
Ti 6Al-4V Nominal	-	-	-	-	-	-	4.0	6.0	-	-	Bal. Ti
Ti 155A Nominal	-	-	-	-	1.4	1.2	-	5.0	-	-	1.5 Fe, Bal. Ti
B 120 VCA Nominal	-	-	-	-	11.0	-	13.0	3.0	-	-	Bal. Ti

Table 14

Summary of Material Variables

Material	Vendor	Heat No.	Form	Direction	Heat Treatment
4340 Steel	Crucible	124515	1" Dia. Bar	L	1700°F Normalize (20 min. salt)
	Acme Co. (Ky.)	7C8236	.070" Sheet	L&T*	Austenitize 1550°F (20 min. salt)
	Ziegler (Cal.)	7C8657	.070" Sheet	L&T	Temper 400°F or 700°F(1 hr. + 1 hr.)
H-11 Steel	Vanadium Alloys	06826	1" Dia. Bar	L	1850°F Austenitize (20 min. salt)
	Vanadium Alloys	05716	.085" Sheet	L&T	Temper at 1000°F, 1050°F, 1100°F. or 1150°F (2 hrs. + 2 hrs.)
18Ni-9Co-5Mo	Vanadium Alloys	06498	.065" Sheet	L&T	1500°F anneal (1 hr., air)
	Allegheny Ludlum	W-24178	.075" Sheet	L&T	Age 900°F (3 hrs.)
18Ni-7Co-5Mo	Vanadium Alloys	06759	1" Dia. Bar	L	1500°F anneal (1 hr., air)
	Allegheny Ludlum	24285	.075" Sheet	L&T	Age 900°F (3 Hrs.)
Beta Titanium	Crucible	F6997	1" Dia. Bar	L	900°F age (72 hours)
	Crucible	F7769	.042" Sheet	L&T	(Vacuum)
	Crucible	F7798	.042" Sheet	L&T	

* Tests in the transverse direction in all cases were made at room temperature only. Longitudinal tests were made over a range of temperatures between -100 and 300°F.

Table 15

Tensile Properties of 4340 Steel Sheet

(280,000 psi Strength Level - Heat 7C-8657)

(400°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi√in)
-100 (long.)	295,800	224,500	11.0	67,200	32,400
	294,900	227,900	10.5	71,200	31,700
				73,600	34,200
Average	295,400	226,200	10.8	70,700	32,800
-45 (long.)	289,000	224,000	11.0	71,900	40,300
	289,000	225,000	13.0	61,100	33,000
				70,200	34,800
Average	289,000	224,500	12.0	67,800	36,000
40 (long.)	283,000	220,000	10.0	94,100	40,000
	283,000	221,000	11.0	80,000	37,900
				78,800	35,500
Average	283,000	220,500	10.5	84,300	37,800
75 (long.)	284,000	222,000	10.0	82,000	32,300
	281,000	225,100	7.0	83,000	36,100
				78,100	37,300
Average	282,500	223,600	8.5	81,000	35,200
75 (trans.)	290,100	223,000	10.0	86,800	35,700
	292,900	224,000	9.5	94,000	36,400
				87,200	35,400
Average	291,500	223,500	9.8	89,400	35,800
200 (long.)	288,000	227,000	9.0	76,400	31,700
	287,600	216,000	10.0	77,200	34,800
				79,900	35,500
Average	287,800	221,500	9.5	77,800	34,000
300 (long.)	288,000	197,000	9.0	67,900	34,000
	290,000	188,000	10.0	71,600	34,400
				66,300	30,800
Average	289,000	192,500	9.5	68,600	33,000

Table 16

Tensile Properties of 4340 Steel Sheet

(280,000 psi Strength Level - Heat 7C-8236)
(400°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100 (long.)	289,800	228,000	13.0	75,100	37,200
	286,900	226,600	12.0	76,100	34,500
				78,600	
Average	288,400	227,300	12.5	76,600	35,800
-45 (long.)	284,000	225,000	12.0	85,600	37,900
	283,000	225,000	11.0	77,100	39,300
				84,500	39,200
Average	283,500	225,000	11.5	82,400	38,800
40 (long.)	279,000	223,000	10.0	95,200	38,200
	280,000	222,000	10.0	98,500	39,100
				102,300	39,900
Average	279,500	222,500	10.0	98,600	39,000
75 (long.)	279,200	219,000	11.0	114,000	46,900
	280,800	217,000	11.0	104,800	45,100
				103,000	42,400
Average	280,000	218,000	11.0	107,200	44,800
75 (trans.)	284,200	225,000	9.0	96,600	39,300
	285,900	223,000	9.0	98,700	38,500
				98,700	42,000
Average	285,000	224,000	9.0	98,000	40,000
200 (long.)	287,000	223,000	10.0	96,600	37,000
	287,000	220,000	10.0	98,300	37,700
				101,000	40,300
Average	287,000	221,500	10.0	98,600	38,300
300 (long.)	290,000	186,000	13.0	83,200	38,800
	286,000	192,500	13.0	77,700	39,400
				79,900	38,500
Average	288,000	189,200	13.0	80,200	38,900

Table 17

Tensile Properties of 4340 Steel Bar

(280,000 psi Strength Level - Heat 124515)

(400°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elong.	Percent Red Area.	Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100	290,700	225,500	15.0	51.2	123,400	40,600
	290,100	225,400	14.0	49.0		
Average	290,400	225,400	14.5	50.1	123,400	40,600
-45	283,500	227,000	15.0	50.1	129,000	41,900
	288,300	221,800	15.0	51.8	121,500	39,800
					139,500	45,600
Average	285,900	224,400	15.0	51.0	130,000	42,400
40	283,300	217,900	15.0	48.4	161,500	52,000
	282,300	221,400	16.0	48.6	147,500	47,900
					180,100	56,500
Average	282,800	219,600	15.5	48.5	163,000	52,100
75	281,900	220,900	15.0	50.7	163,000	51,600
	280,700	221,000	16.0	49.0	183,000	59,600
					176,000	55,400
Average	281,300	221,000	15.5	49.8	174,000	55,500
200	285,500	216,900	14.0	41.3	135,000	47,200
	282,300	216,500	13.5	42.0	148,000	49,200
					154,500	48,400
Average	283,900	216,700	13.8	41.6	145,000	48,300
300	288,100	192,000	18.0	45.5	127,000	39,900
	289,900	198,000	19.0	41.3	137,000	43,600
					132,000	42,000
Average	289,000	195,000	18.5	43.4	132,000	41,800

Table 18

Tensile Properties of 4340 Steel Sheet

(210,000 psi Strength Level - Heat 7C-8657)

(750°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{\text{in}}$)
-100 (long.)	223,800	209,000	9.5	93,000	50,600
	224,700		10.0	91,200	47,600
				85,600	47,300
Average	224,200	209,000	9.8	89,900	48,500
-45 (long.)	219,000	207,000	8.0	159,000	58,400
	219,000	203,000	10.0	167,000	66,600
				158,000	57,900
Average	219,000	205,000	9.0	161,400	61,000
40 (long.)	213,000	199,000	10.0	157,000	51,300
	209,000	196,000	9.0	155,000	57,200
				163,000	60,000
Average	211,000	197,500	9.5	158,400	56,200
75 (long.)	214,300	200,500	7.5	151,800	63,900
	212,200	196,600	8.0	156,400	59,000
				151,800	64,500
Average	213,200	198,600	7.8	153,400	62,400
75 (trans.)	210,100	194,600	7.5	127,000	55,500
	212,200	196,100	8.0	139,600	52,600
				128,800	45,800
Average	211,200	195,400	7.8	131,800	51,300
200 (long.)	207,500	184,700	9.0	171,000	67,200
	207,500	182,500	8.5	149,200	63,500
				146,600	61,000
Average	207,500	183,600	8.8	155,600	63,900
300 (long.)	209,300	180,300	9.0	134,800	50,800
	207,100	175,600	9.0	142,800	41,600
				146,200	54,100
Average	208,200	178,000	9.0	141,200	48,800

Table 19

Tensile Properties of 4340 Steel Sheet

(210,000 psi Strength Level - Heat 7C-8236)
(750°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-190 (long.)				83,600	43,100
-100 (long.)	226,700	213,900	10.0	145,500	63,900
	223,300	209,500	9.5	160,000	68,200
				154,700	62,700
Average	225,000	211,700	9.8	153,400	64,900
-45 (long.)	219,000	209,000	9.0	172,000	75,600
	219,500	205,000	10.0	170,000	72,100
					81,000
Average	219,200	207,000	9.5	171,000	76,200
40 (long.)	213,000	197,500	9.0	160,500	86,900
	212,000	197,500	8.0	173,000	79,500
				170,300	71,200
Average	212,500	197,500	8.5	168,000	79,200
75 (long.)	213,700	199,200	9.0	180,100	71,900
	210,400	196,500	10.0	166,500	64,900
				163,200	75,400
Average	212,000	197,800	9.5	170,000	70,800
75 (trans.)	213,400	199,600	9.0	142,000	51,500
	211,500	196,600	8.0	140,800	50,400
				126,000	53,100
Average	212,400	198,100	8.5	136,200	51,600
200 (long.)	206,200	184,800	8.0	145,000	59,200
	208,000	185,300	7.5	148,400	70,000
				151,600	69,400
Average	207,100	185,000	7.8	148,400	66,200
300 (long.)	209,200	174,100	9.0	145,200	64,000
	206,600	178,200	8.5	151,100	63,100
				146,900	
Average	207,900	176,200	8.8	147,800	63,600

Table 20

Tensile Properties of 4340 Steel Bar

(210,000 psi Strength Level - Heat 124515)

(750°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elong.	Percent Red Area.	Notch Tensile Strength (psi)	Plane Strain* Fracture Toughness (psi$\sqrt{in}$)
-100	223,700	208,700	13.0	51.2	230,100	74,500
	224,700	210,700	14.0	51.2	239,900	78,500
Average	224,200	209,700	13.5	51.2	235,000	76,500
-45	221,300	205,700	14.0	50.7	255,000	90,100
	220,500	206,800	14.0	50.7	260,000	86,600
Average	220,900	206,200	14.0	50.7	257,500	88,300
40	212,500	200,000	14.5	51.8	248,000	85,500
	212,300	198,300	14.5	51.8	274,000	97,500
					263,000	90,600
Average	212,400	199,200	14.5	51.8	262,000	91,200
75	212,500	197,500	14.0	53.9	264,000	93,400
	213,500	198,200	13.0	48.4	273,000	97,400
					252,000	85,000
Average	213,000	197,800	13.5	51.2	263,000	91,900
200	210,300	185,400	14.5	51.8	226,000	75,100
	207,300	184,600	14.0	50.7	233,000	80,500
					223,000	75,100
Average	208,800	185,000	14.2	51.2	227,000	76,900
300	207,700	173,000	16.0	53.4	197,000	66,400
	209,500	178,400	15.0	46.1	226,000	74,600
					232,000	87,000
Average	208,600	175,700	15.5	49.8	218,000	76,000

* $\sigma_N > 1.1\ F_{TY}$

Table 21

Tensile Properties of H-11 Steel Bar

(295,000 psi Strength Level - Heat 06826)

(1000°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elong.	Percent Red. Area	Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-45	309,100	251,200	12.0	34.1	69,300	20,600
	308,300	251,900	14.0	37.9	72,800	22,400
					71,200	22,200
Average	308,700	251,600	13.0	36.0	71,100	21,700
40	300,700	216,400	12.5	37.6	80,400	24,500
	302,300		13.0	37.3	82,300	28,500
					85,800	26,800
Average	301,500	216,400	12.8	37.4	82,800	26,600
75	296,700	241,800	13.0	40.4	74,100	23,200
	298,500	238,100	13.0	39.1	87,400	27,500
					84,000	24,400
Average	297,600	240,000	13.0	39.8	81,800	25,000
200	286,900	226,700	14.0	42.0	105,900	34,000
					114,400	36,700
Average	286,900	226,700	14.0	42.0	110,200	35,400
300	277,800	227,800	13.5	44.0	133,300	43,100
					120,000	37,700
Average	277,800	227,800	13.5	44.0	126,600	40,400

Table 22

Tensile Properties of H-11 Steel Sheet

(290,000 psi Strength Level - Heat 05716)

(1000°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100 (long.)	311,300	263,500	11.0	36,800	24,300
	305,600	251,700	7.5	38,200	26,100
				37,800	25,800
Average	308,400	257,600	9.2	37,600	25,400
-45 (long.)	299,200	247,900	10.0	35,200	24,100
	301,700	247,500	9.5	38,900	26,000
				40,400	23,400
Average	300,400	247,700	9.8	38,200	24,500
40 (long.)	291,200	237,200	10.0	50,900	27,800
	292,100	243,100	10.0	51,400	30,700
				54,200	30,000
Average	291,600	240,200	10.0	52,200	29,500
75 (long.)	292,500	241,600	9.0	61,900	30,000
	290,500	244,200	10.0	55,400	30,200
				62,400	30,400
Average	291,500	242,900	9.5	59,900	30,200
75 (trans.)	285,500	235,300	9.0	57,700	29,500
	288,200	235,000	10.5	67,600	28,400
				59,300	28,100
Average	286,800	235,200	9.8	61,500	28,700
200 (long.)	281,200	232,100	10.5	130,600	41,800
	282,500	231,000	11.0	118,100	46,000
				144,800	39,800
Average	281,800	231,600	10.8	131,200	42,500
300 (long.)	275,300	232,200	11.0	160,100	51,400
	273,500	228,500	11.0	161,200	53,600
				127,000	50,000
				159,700	47,600
Average	274,400	230,400	11.0	152,000	50,600

Table 23

Tensile Properties of H-11 Steel Bar

(270,000 psi Strength Level - Heat 06826)
(1050°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elong.	Percent Red. Area	Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-45	282,700	233,600	13.0	41.3	79,900	26,500
	279,700	236,600	12.5	41.3	93,700	28,700
					87,700	26,600
Average	281,200	235,100	12.8	41.3	87,100	27,300
40	270,200	230,200	14.5	45.5	98,800	31,600
	275,500	226,300	13.0	44.3	98,700	31,600
					105,000	34,500
Average	272,800	228,200	13.8	44.9	100,800	32,600
75	270,900	230,300	14.0	46.1	106,900	35,200
	269,200	226,100	15.0	45.5	107,300	34,800
					110,000	34,500
Average	270,000	228,200	14.5	45.8	108,100	34,800
200	263,800	219,700	15.0	45.5	144,800	44,300
					144,000	44,700
Average	263,800	219,700	15.0	45.5	144,400	44,500
300	252,800	214,700	14.0	49.0	162,800	48,700
					161,300	49,200
Average	252,800	214,700	14.0	49.0	162,000	49,000

Table 24

Tensile Properties of H-11 Steel Sheet

(260,000 psi Strength Level - Heat 05716)

(1050°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100 (long.)	280,000	239,000	10.0	44,400	30,300
	280,900	241,400	10.0	47,200	32,200
				41,600	28,500
Average	280,400	240,200	10.0	44,300	30,300
-45 (long.)	269,600	230,800	9.5	44,800	30,600
	272,100	231,900	11.5	45,600	26,300
				47,300	32,200
Average	270,800	231,400	10.5	45,900	29,700
40 (long.)	266,700	227,800	11.0	70,500	34,500
	261,100	222,900	10.0	68,900	38,000
				70,200	32,800
Average	263,900	225,400	10.5	69,900	35,100
75 (long.)	260,800	223,600	11.0	77,000	32,000
	262,400	222,700	12.0	78,100	31,800
				82,400	36,800
Average	261,600	223,200	11.5	79,200	33,500
75 (trans.)	267,000	222,200	10.5	93,100	37,600
	263,900	223,900	11.0	90,700	35,600
				85,200	37,500
Average	265,400	223,000	10.8	89,700	36,900
200 (long.)	255,200	214,200	12.0	187,300	52,800
	255,400	215,100	10.0	192,200	57,200
				186,400	47,800
				194,100	58,100
Average	255,300	214,600	11.0	190,000	54,000
300 (long.)	248,700	215,300	11.0	185,000	61,600
	250,400	208,700	11.0	191,400	58,300
				188,900	59,400
Average	249,600	212,000	11.0	188,400	59,800

Table 25

Tensile Properties of H-11 Steel Bar
(230,000 psi Strength Level - Heat 06826)
(1100°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elong.	Percent Red. Area	Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-45	243,400	207,000	16.0	46.9	135,300	42,000
	246,000	208,400	15.0	46.7	131,100	42,300
					153,400	47,600
Average	244,700	207,700	15.5	46.8	139,900	44,000
40	234,800	200,000	15.0	46.3	221,000*	69,600**
	236,400	198,400	15.0	48.6		
Average	235,600	199,200	15.0	47.4	221,000	69,600
75	230,400	193,300	14.5	49.7		
Average	230,400	193,300	14.5	49.7		
200	224,900	190,900	15.5	50.1	215,600	66,600**
					160,800	50,000+
					192,700	59,500+
Average	224,900	190,900	15.5	50.1	189,700	58,700
300	222,200	188,300	15.0	52.0	248,000	86,200**
Average	222,200	188,300	15.0	52.0	248,000	86,200

* - Very shallow precrack

** - $\sigma_N > 1.10\ F_{TY}$

\+ - Possible eccentricity in loading

Table 26 ER-5426

Tensile Properties of H-11 Steel Sheet

(225,000 psi Strength Level - Heat 05716)

1100°F Temper

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100 (long.)	238,500	202,400	10.0	55,100	38,000
	239,600	203,000	12.5	57,200	39,200
				50,700	34,900
Average	239,000	202,700	11.2	54,300	37,400
-45 (long.)	233,200	198,600	14.0	96,800	31,400
	233,500	193,900	13.0	98,700	35,700
				76,300	33,300
Average	233,400	196,200	13.5	90,600	33,500
40 (long.)	223,500	190,700	13.0	192,700	74,100
	227,600	193,800	12.0	187,200	77,900
				197,300	80,300
Average	225,600	192,200	12.5	192,400	77,400
75 (long.)	222,900	191,200	14.5	192,600	86,300
	223,400	186,400	13.0	190,900	77,000
				190,200	98,900
Average	223,200	188,800	13.8	191,200	87,400
75 (trans.)	225,500	190,400	12.5	182,300	85,400
	222,100	185,400	14.5	189,500	85,600
				189,900	89,000
Average	223,800	187,900	13.5	187,200	86,700
200 (long)	217,000	180,900	12.0	183,300	91,600
	217,000	183,900	13.5	188,600	86,400
				190,200	81,400
Average	217,000	182,400	12.8	189,400	86,500
300 (long)	213,900	169,500	12.0	181,400	82,700
	211,100	167,800	12.5	175,300	97,400
				170,000	82,400
				194,200	84,900
Average	212,500	168,600	12.2	180,200	86,800

Table 27

Tensile Properties of H-11 Steel Bar

(195,000 psi Strength Level - Heat 06826)

(1150°F Temper)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elong.	Percent Red. Area	Notch Tensile Strength (psi)	Plane Strain* Fracture Toughness (psi$\sqrt{in}$)
-45	209,300	158,800	16.0	49.7	191,100	58,100
	204,700	167,200	16.0	49.2	210,200	69,200
Average	207,000	163,000	16.0	49.4	200,600	63,600
40	202,300	168,800	16.0	53.6	231,200	78,600
	192,800	156,000	16.0	52.2	244,700	87,100
Average	197,600	162,400	16.0	52.9	238,000	82,800
75	195,700	163,100	15.0	51.4		
Average	195,700	163,100	15.0	51.4		
200	188,200	155,500	15.0	52.7	261,800	**
					223,400	77,200
Average	188,200	155,500	15.0	52.7	242,600	77,200
300	179,700	148,200	16.0	54.1	247,600	**
					244,300	
					238,700	
Average	179,700	148,200	16.0	54.1	243,500	

* $\sigma_N > 1.10\ F_{TY}$ in all tests.

** σ_N/F_{TY} value too high to find K_{IC} from graphical method.

Table 28 ER-5426

Tensile Properties of H-11 Steel Sheet

(195,000 psi Strength Level - Heat 05716)

1150°F Temper

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi√in)
-100 (long.)	208,900	172,800	17.0	102,800	50,300
	207,800	167,400	15.0	124,800	61,900
				177,800	75,700
Average	208,400	170,100	16.0	135,100	62,600
-45 (long.)	204,000	164,700	14.0	155,800	101,600
	202,100	164,200	15.5	175,900	90,800
				189,600	103,900
Average	203,000	164,400	14.8	173,800	98,800
40 (long.)	197,500	160,000	14.0	172,800	95,600
	199,300	160,300	13.0	172,700	93,200
				174,500	99,300
Average	198,400	160,200	13.5	173,300	96,000
75 (long.)	194,600	157,800	14.5	170,300	94,400
	193,000	156,700	13.5	174,000	93,700
				174,600	87,400
Average	193,800	157,200	14.0	173,000	91,800
75 (trans.)	196,900	161,900	13.0	169,000	91,500
	196,300	160,200	13.5	174,600	87,600
				175,000	88,900
Average	196,600	161,000	13.2	172,900	89,400
200 (long)	188,200	154,400	12.5	173,100	93,700
	187,800	154,100	12.5	179,000	88,200
				179,800	79,100
Average	188,000	154,200	12.5	177,300	87,000
300 (long)	181,900	151,700	12.0	177,300	94,900
	182,300	147,700	13.0	171,700	83,500
				177,400	101,400
Average	182,100	149,700	12.5	175,500	93,300

Table 29

Tensile Properties of 18% Nickel Maraging Steel Bar

(250,000 psi Strength Level - Heat 06759)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elong.	Percent Red. Area.	Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-100	283,700 278,100	276,700 271,600	9.5 9.5	45.1 44.5	151,100	47,700
Average	280,900	274,200	9.5	44.8	151,100	47,700
-45	268,900 272,300	260,500 262,500	10.5 11.0	45.5 47.3	113,900 107,200	42,300 36,600
Average	270,600	261,500	10.8	46.4	110,600	39,400
40	261,700 266,100	256,500 258,500	11.0 11.0	48.5 49.1	114,500 148,500	36,100 45,900
Average	263,900	257,500	11.0	48.8	131,500	41,000
75	263,000 263,300	257,000 255,200	11.0 11.0	50.9 47.6	224,500 215,600 165,400	72,400 68,500 52,200
Average	263,200	256,100	11.0	49.2	201,500	64,400
200	255,600 254,800	244,600 248,900	11.0 11.5	49.9 50.9	191,100 211,500 204,500	59,700 68,400 65,300
Average	255,200	246,800	11.2	50.4	202,400	64,500
300	243,600 246,800	235,600 238,400	11.0 12.0	49.9 51.8	292,200 335,800	94,600* 112,400*
Average	245,200	237,000	11.5	50.8	314,000	103,500

* $\sigma_N > 1.10\ F_{TY}$

Table 30

Tensile Properties of 18% Nickel Maraging Steel Sheet
(250,000 psi Strength Level-Heat 24285)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi√in)	
					High K_{IC}	Low K_{IC}
-100 (long)	250,800	245,400	6.5	209,000	90,400	74,900
	254,800	250,800	7.0	221,900	92,200	73,500
				224,000	94,200	
Average	252,800	248,100	6.8	218,300	92,300	74,200
-45 (long)	248,500	240,900	7.5	214,200	148,800	87,100
	252,000	240,000	8.5		151,900	100,300
					155,400	78,100
Average	250,200	240,400	8.0	214,200	152,000	88,500
40 (long)	239,200	227,000	8.0	206,600	166,200	98,10C
	237,900		8.0	205,200	145,800	80,700
				204,700	144,700	74,100
Average	238,600	227,000	8.0	205,500	152,200	84,300
75 (long)	237,200	229,600	7.5	209,500	144,700	97,400
	236,300	229,500	8.0	209,400	148,200	84,400
					144,400	94,200
					144,700	92,100
Average	236,800	229,600	7.8	209,400	145,500	92,000
75 (trans.)	241,900	233,200	7.5	183,500	121,900	69,300
	241,300	233,000	7.5	182,500	119,600	69,900
				189,000	116,700	68,000
				181,400	131,200	71,100
Average	241,600	233,100	7.5	184,100	122,400	69,600
200 (long)	227,600	220,400	8.5	198,800	139,200	86,500
	228,300	222,200	8.0	200,700	130,900	74,400
					133,200	83,300
					139,200	87,900
Average	228,000	221,300	8.2	199,800	135,600	83,000
300 (long)	221,700	211,900	7.5	182,500	131,700	89,900
	221,100	213,100	8.0	184,500	125,300	78,100
				186,000		87,400
				184,100		
Average	221,400	212,500	7.8	184,300	128,500	85,100

Table 31

Tensile Properties of 18% Nickel Maraging Steel Sheet

(300,000 psi Strength Level - Heat 06498)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi√in) High K_{IC}	Plane Strain Fracture Toughness (psi√in) Low K_{IC}
-100 (long)	285,700	277,600	6.0	194,600	95,100	72,900
	285,500	274,800	6.5	187,400	87,400	69,000
				193,100	79,400	72,400
Average	285,600	276,200	6.2	191,700	87,300	71,400
-45 (long)	277,500	266,100	6.0	194,600	115,500	85,100
	279,000	266,000	6.5	184,900	120,100	77,200
				204,200		82,300
Average	278,200	266,000	6.2	194,600	117,800	81,500
40 (long.)	266,000	253,100	7.0	182,100	111,400	79,600
	266,000	252,900	7.0	205,500	113,700	82,700
				192,500	121,200	72,400
				186,400		
Average	266,000	253,000	7.0	191,600	115,400	78,200
75 (long)	262,800	251,700	7.5	190,100	115,000	75,100
	265,800	250,200	6.5	185,400	118,600	74,500
				182,700	116,600	75,100
				180,000	117,800	71,900
Average	264,300	251,000	7.0	184,600	117,000	74,200
75 (trans.)	266,900	254,800	6.5	183,700	110,600	72,500
	268,700	259,300	7.0	192,400	98,600	73,900
				184,000	103,700	75,200
				182,400		
Average	267,800	257,000	6.8	185,600	104,300	73,900
200 (long)	253,100	244,000	6.5	178,000	114,600	77,100
	253,500	242,000	6.0	178,600	116,000	82,900
				183,300	111,600	76,500
				186,600	112,500	74,800
Average	253,300	243,000	6.2	181,600	113,700	77,800
300 (long)	249,400	236,800	6.5	177,900	117,000	74,500
	247,700	237,800	6.5	179,300	120,600	76,000
				168,300		76,200
				174,400		
Average	248,600	237,300	6.5	177,700	118,800	75,600

Table 32

Tensile Properties of 18% Nickel Maraging Steel Sheet

(300,000 psi Strength Level - Heat W-24178)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$) High K_{IC}	Plane Strain Fracture Toughness (psi$\sqrt{in}$) Low K_{IC}
-100 (long)	294,800	289,100	7.0	173,100	86,600	65,400
	292,700	285,100	7.5	177,100	99,100	75,600
				184,500	76,000	
Average	293,800	287,100	7.2	178,200	87,200	70,500
-45 (long)	285,900	277,900	8.0	168,700	105,000	67,200
	284,800	276,100	7.0	178,400	115,600	65,500
				182,700	115,500	
Average	285,400	277,000	7.5	176,600	112,000	66,400
40 (long)	274,000	265,700	6.0	169,700	104,000	71,800
	274,500	264,000	7.5	156,500	99,000	68,400
				171,000	109,600	67,200
Average	274,200	264,800	6.8	165,700	104,200	69,100
75 (long)	275,100	267,400	7.5	173,800	113,300	71,500
	272,400	265,600	7.0	177,300	115,600	70,300
				181,500	124,500	73,400
Average	273,800	266,500	7.2	177,500	117,800	71,700
75 (trans.)	278,300	269,800	6.5	163,600	101,900	69,600
	277,900	271,500	7.0	165,100	110,200	70,000
				167,100	104,600	67,700
Average	278,100	270,600	6.8	165,300	105,600	69,100
200 (long)	258,800	248,900	6.5	170,700	106,500	71,200
	262,300	256,900	7.0	165,800	99,900	73,000
				176,500	100,700	83,300
				173,400		
Average	260,600	252,900	6.8	171,600	102,400	75,800
300 (long)	255,000	242,900	6.5	174,200	122,100	80,700
	253,800	244,600	6.5	166,900	114,400	83,200
				174,800	113,200	67,400
Average	254,900	243,800	6.5	172,000	116,600	77,100

Table 33

Tensile Properties of Beta Titanium (B120 VCA) Bar

(200,000 psi Strength Level-Heat F 6997)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elong.	Percent Red Area.	Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{in}$)
-45	217,100	200,700	8.0	8.1	88,900	28,900
	214,700	200,300	5.0	5.1	87,000	26,500
					88,500	27,800
Average	215,900	200,500	6.5	6.6	88,100	27,700
40	200,500	183,400	6.0	4.7	106,000	34,600
	197,000	180,500	7.0	6.6	101,200	32,300
					101,500	32,900
Average	198,800	182,000	6.5	5.6	102,900	33,300
75	198,700	179,400	11.0	9.7	94,400	30,600
	198,100	183,400	3.5	3.1	96,200	32,300
					106,700	32,600
Average	198,400	181,400	7.2	6.4	99,100	31,900
200	192,900	165,200	9.0	7.8	111,000	35,700
	189,000	161,500	12.5	14.4	119,000	36,300
					121,500	41,700
Average	191,000	163,400	10.8	11.3	117,000	37,900
300	191,700	159,400	11.0	13.8	123,500	40,700
	191,700	159,000	10.0	13.8	120,500	38,600
					121,900	38,100
Average	191,700	159,200	10.5	13.8	122,000	39,100

Table 34
Tensile Properties of Beta Titanium (B120VCA) Sheet

(170,000 psi Strength Level - Heat F 7798)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi$\sqrt{\text{in}}$)
-100 (long.)	174,400	174,400	6.5	38,800	23,300
	166,100	158,000	7.0	37,100	22,900
				41,200	27,100
Average	170,200	166,200	6.8	39,000	24,400
-45 (long.)	186,800	182,400	1.0	38,600	22,700
	172,800		1.5	42,100	23,200
				39,800	24,200
Average	179,800	182,400	1.2	40,200	23,400
40 (long.)	172,700	169,500	2.0	47,600	28,800
				46,700	24,500
				47,000	32,000
Average	172,700	169,500	2.0	47,100	28,400
75 (long.)	170,500	166,000	1.0	62,800	31,600
	167,500	165,300	1.0	57,400	29,200
				59,600	29,000
Average	169,000	165,600	1.0	60,000	30,000
75 (trans.)	139,000	139,000	1.5	50,900	29,500
	136,600	136,600		56,500	29,700
				54,200	33,000
Average	137,800	137,800	1.5	53,800	30,800
200 (long.)	168,600	153,600	3.5	71,400	41,700
	166,700	153,600	3.0	81,400	43,100
				71,300	43,400
Average	167,600	153,600	3.2	74,700	42,800
300 (long.)	167,900	145,300	4.0	87,600	44,100
	172,100	146,700	5.0	87,400	41,400
				70,900	35,100
Average	170,000	146,000	4.5	82,000	40,200

Table 35

Tensile Properties of Beta Titanium (B120 VCA) Sheet

(185,000 psi Strength Level - Heat F7769)

Test Temperature (°F)	Tensile Strength (psi)	0.2% Yield Strength (psi)	Percent Elongation	Net Notch Tensile Strength (psi)	Plane Strain Fracture Toughness (psi√in)
-100 (long.)				36,000	21,400
				36,100	24,000
Average				36,000	22,700
-45 (long.)	198,200	194,900	2.0	40,300	23,500
	209,300	207,900	2.0	40,600	27,400
				40,600	25,800
Average	203,800	200,400	2.0	40,500	25,600
40 (long.)	189,300	180,100	3.0	40,000	23,400
	192,900	185,500	2.5	46,100	26,200
				47,800	27,200
Average	191,100	182,800	2.8	44,600	25,600
75 (long.)	185,800	174,300	3.5	56,200	33,900
	188,700	174,500	4.0	45,400	25,700
				52,800	30,600
Average	187,300	174,400	3.8	51,500	30,000
75 (trans.)	188,300	181,100	3.0	42,600	27,600
	193,400	183,600	2.0	43,000	24,100
Average	190,800	182,400	2.5	42,800	25,800
200 (long.)	183,300	161,800	5.0	68,000	32,300
	176,400	158,600	4.0	66,400	31,800
				63,800	36,000
Average	179,800	160,200	4.5	66,000	33,400
300 (long.)	182,500	159,100	5.0	69,700	34,800
	171,200	155,100	3.5	78,800	39,700
	177,600	154,100		83,100	41,700
				79,800	
Average	177,100	156,100	4.2	77,800	38,700

Table 36

(Handbook TABLE 2.3.1.1(a)) DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF AISI ALLOY STEELS

Alloy	AISI 4130, 8630, and 8735		AISI 4130, 4140, 4340 8630, 8735, and 8740			4140 4340 8740	AISI 4340
Form	Sheet, strip plate, tubing		All wrought forms				
Condition			Heat treated (quenched and tempered) to obtain F_{tu} indicated				
Thickness or diameter, in.	0.187	0.187	See Table 2.3.0.1 (a)				
Basis							(a)
Mechanical Properties							
F_{tu}, ksi	95	90	125	150	180	200	260
F_{ty}, ksi	75	70	103	132	163	176	217
F_{cy}, ksi	75	70	113	145	179	198	242
F_{su}, ksi	55	55	82	95	109	119	149
F_{bru}, ksi							
(e/D=1.5)	--	--	194	219	250	272	347
(e/D=2.0)	140	140	251	287	326	351	440
F_{bry}, ksi							
(e/D=1.5)	--	--	151	189	230	255	312
(e/D=2.0)	--	--	180	218	256	280	346
e, per cent	See Table 2.3.1.1 (b)		See Table 2.3.1.1 (c)				L 10 (b) T 3 (b)
K_{IC}^{*}, psi/in. (L)	--	--	--	--	--	100,000	46,000
(T)	--	--	--	--	--	80,000	40,000
E, 10^6 psi	--	29.0	--	--	--	--	--
E_c, 10^6 psi	--	29.0	--	--	--	--	--
G, 10^6 psi	--	11.0	--	--	--	--	--
Physical Properties							
w, lb/in.^{3}	0.283						
C, Btu/(lb)(F)	0.114 (at 32F)						
K, Btu/(hr)(ft^2)(F)/ft	22.0 (at 32F)						
a, 10^{-6} in./in./F	6.3 (0 to 200F)						

* Data obtained for 4340 steel

Table 37

(Handbook TABLE 2.5.1.1.) DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 5Cr-Mo-V AIRCRAFT STEEL

Alloy	5Cr-Mo-V Aircraft Steel		
Form	All wrought forms		
Condition	Heat treated to obtain the F_{tu} indicated.		
Section Size	Up to 12 in. diam. or equivalent		
Basis	(a)	(a)	(a)
Mechanical Properties			
F_{tu}, ksi	240	260	280
F_{ty}, ksi	200	220	240
F_{cy}, ksi	220	240	260
F_{su}, ksi	145	155	170
F_{bru}, ksi			
(e/D=1.5)	--	--	--
(e/D=2.0)	400	435	465
F_{bry}, ksi			
(e/D=1.5)	--	--	--
(e/D=2.0)	315	340	365
e, per cent Bar, in 4D	9	8	7
Sheet, in 2 in. (a)	6	5	4
Sheet, in 1 in.	8	7	6
K_{IC}, psi√in. L	73,000	46,000	32,000
T	68,000	40,000	28,000
E, 10^6 psi		30.0	
E_c, 10^6 psi		30.0	
G, 10^6 psi		11.0	
Physical Properties			
w, lb/in.^{3}	0.281		
C, Btu/(lb) (F)	0.11$^{(c)}$ (32F)		
K, Btu/ (hr) (ft^2)(F)/ft	16.6 (400 to 1100F)		
a, 10^{-6}in./in./F	7.1 (80 to 800F); 7.4 (80-1200F)		

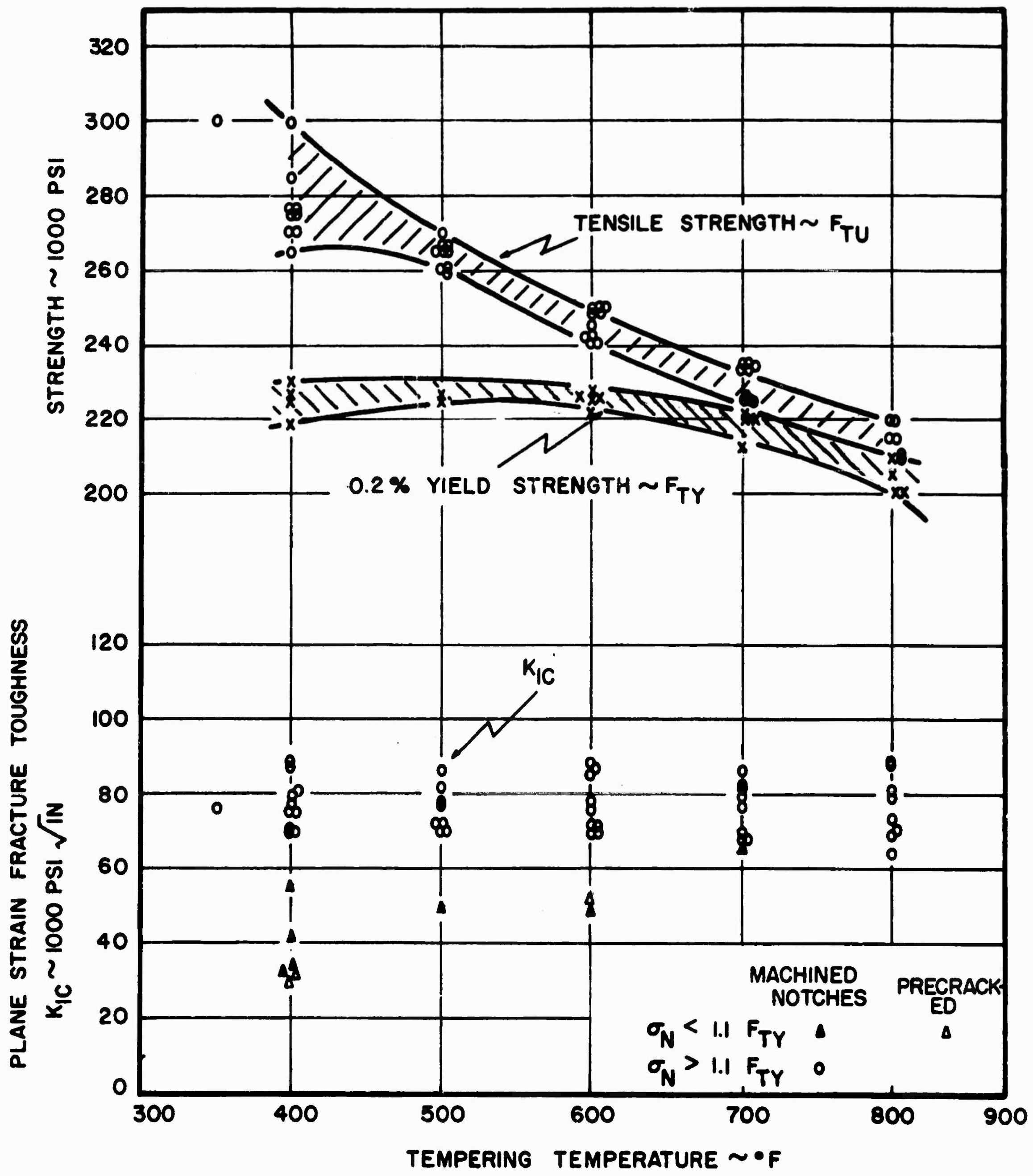

FIG. 1: INFLUENCE OF TEMPERING TEMPERATURE ON THE SMOOTH STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF 4340 STEEL AT ROOM TEMPERATURE, LONGITUDINAL ORIENTATION, (DATA FROM TABLE 2).

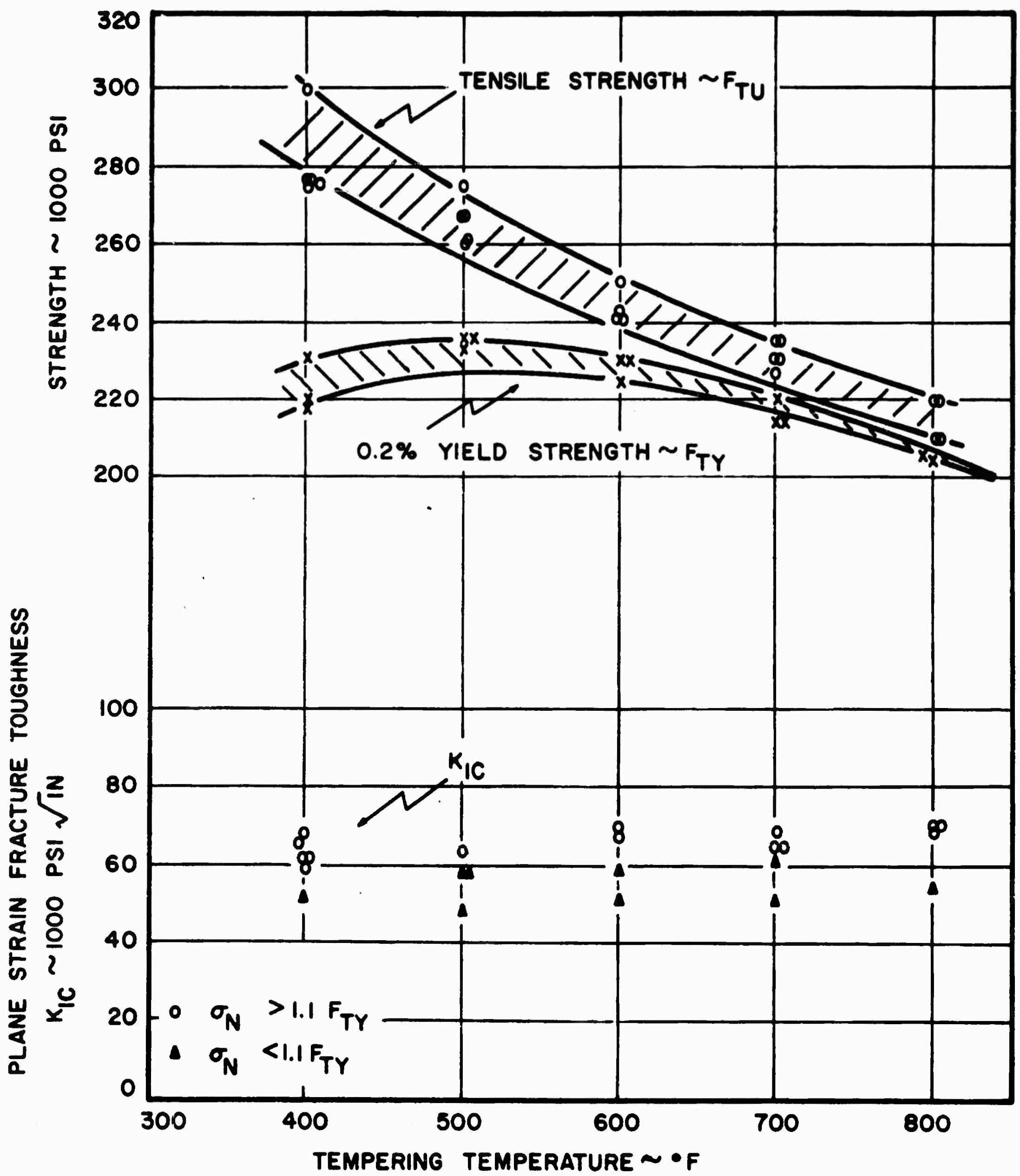

FIG. 2: INFLUENCE OF TEMPERING TEMPERATURE ON THE SMOOTH STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF 4340 STEEL AT ROOM TEMPERATURE, TRANSVERSE ORIENTATION, (DATA FROM TABLE 3), ALL SPECIMENS CONTAIN MACHINED NOTCHES.

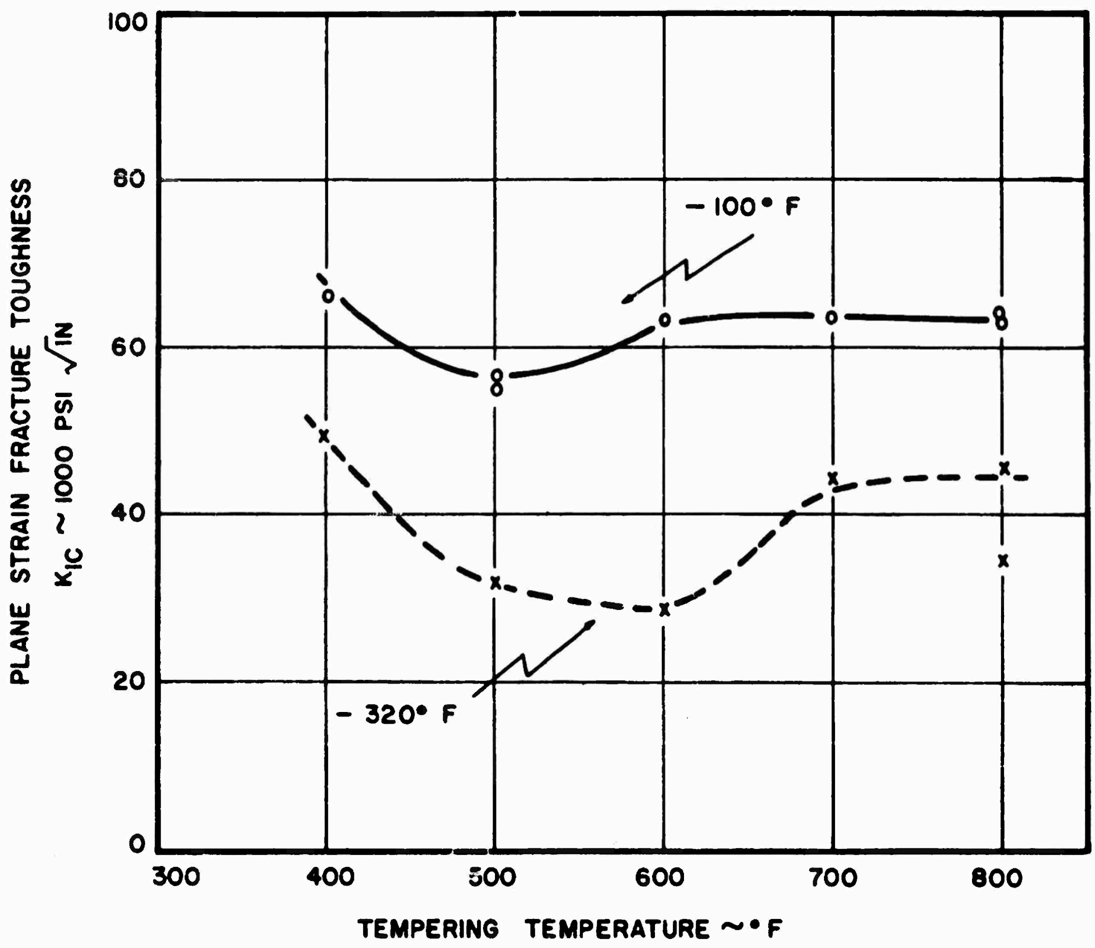

FIG. 3: VARIATION OF K_{IC} WITH TEST TEMPERATURE, 4340 STEEL. (SEE TABLE 4), MACHINED NOTCHES.

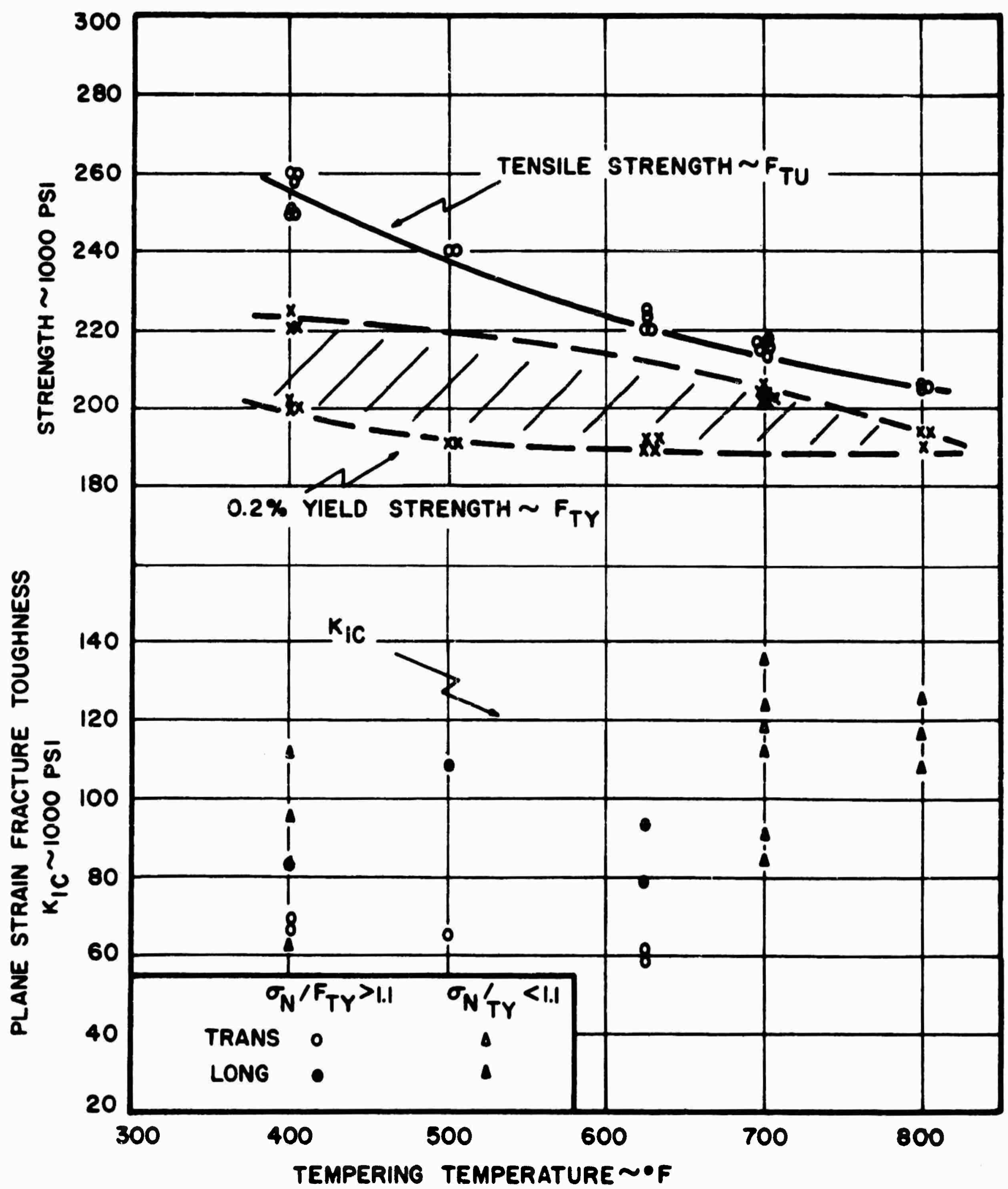

FIG. 4: INFLUENCE OF TEMPERING TEMPERATURE ON THE SMOOTH STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF MOD. 4330 STEEL AT ROOM TEMPERATURE. (SEE TABLE 5), MACHINED NOTCHES.

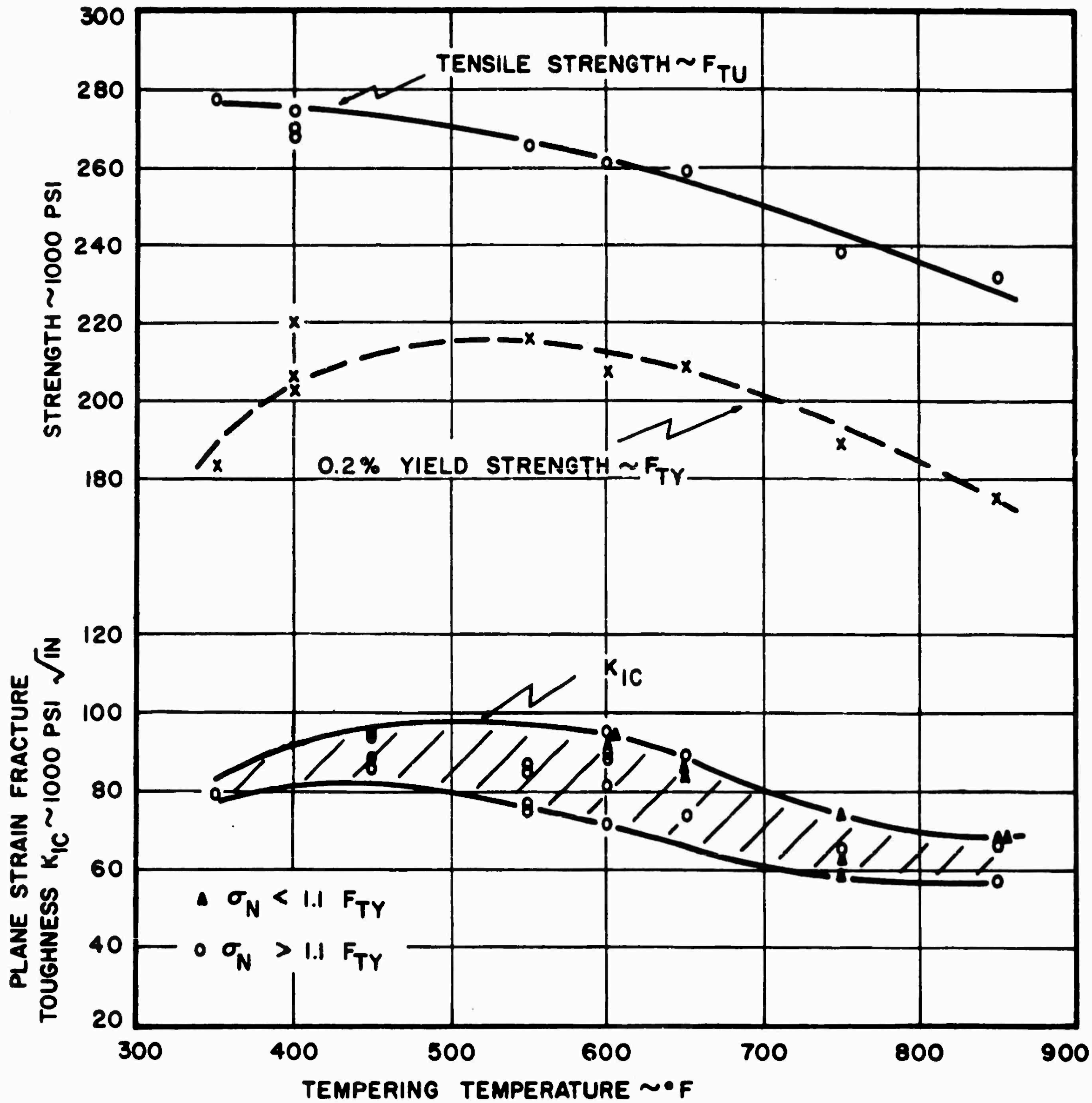

FIG. 5: INFLUENCE OF TEMPERING TEMPERATURE ON THE SMOOTH STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF 4330 (MOD Si+V) STEEL AT ROOM TEMPERATURE. (SEE TABLE 6), MACHINED NOTCHES.

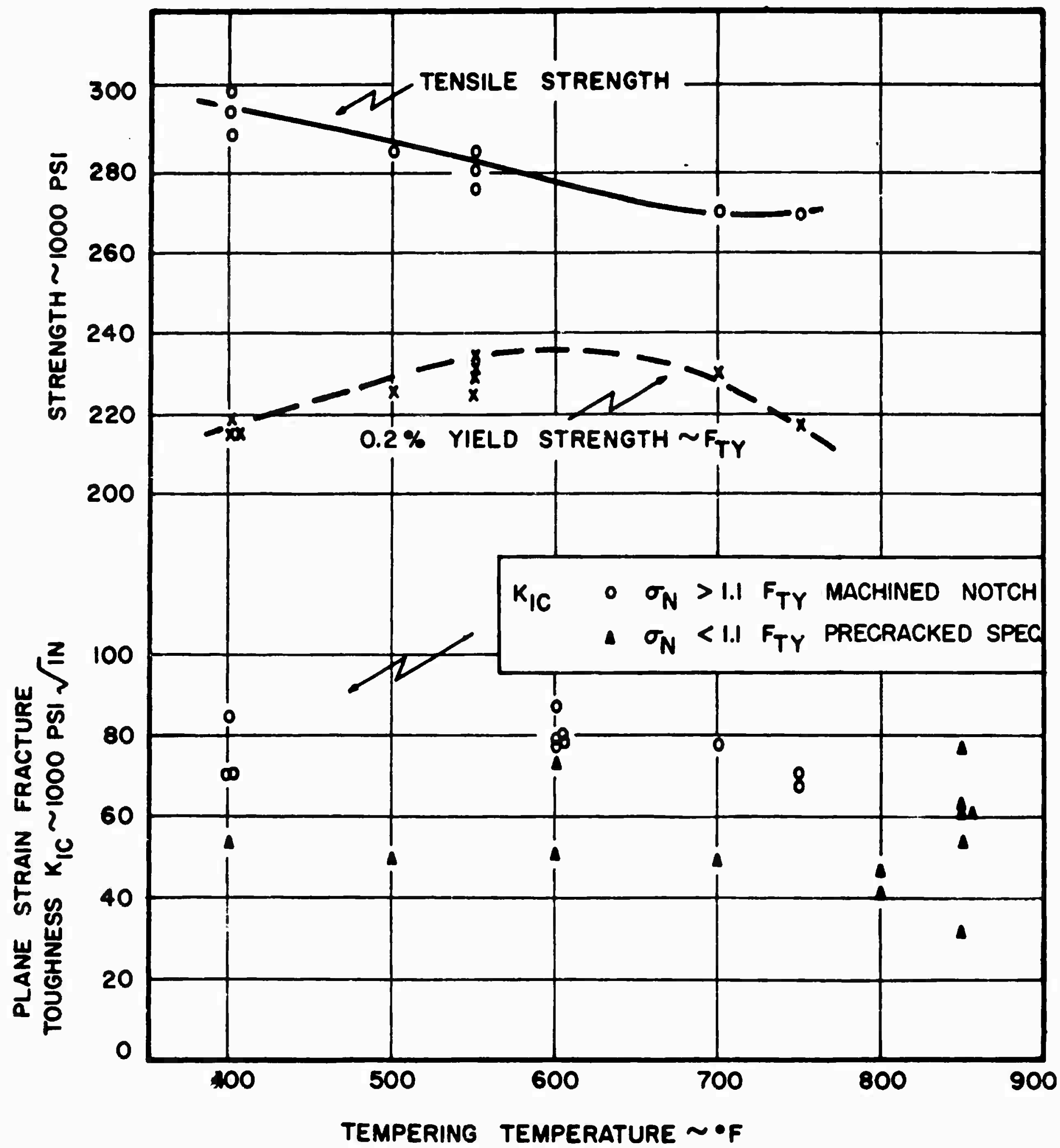

FIG. 6: INFLUENCE OF TEMPERING TEMPERATURE ON THE SMOOTH STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF 300 M STEEL, LONGITUDINAL DIRECTION. (SEE TABLE 7).

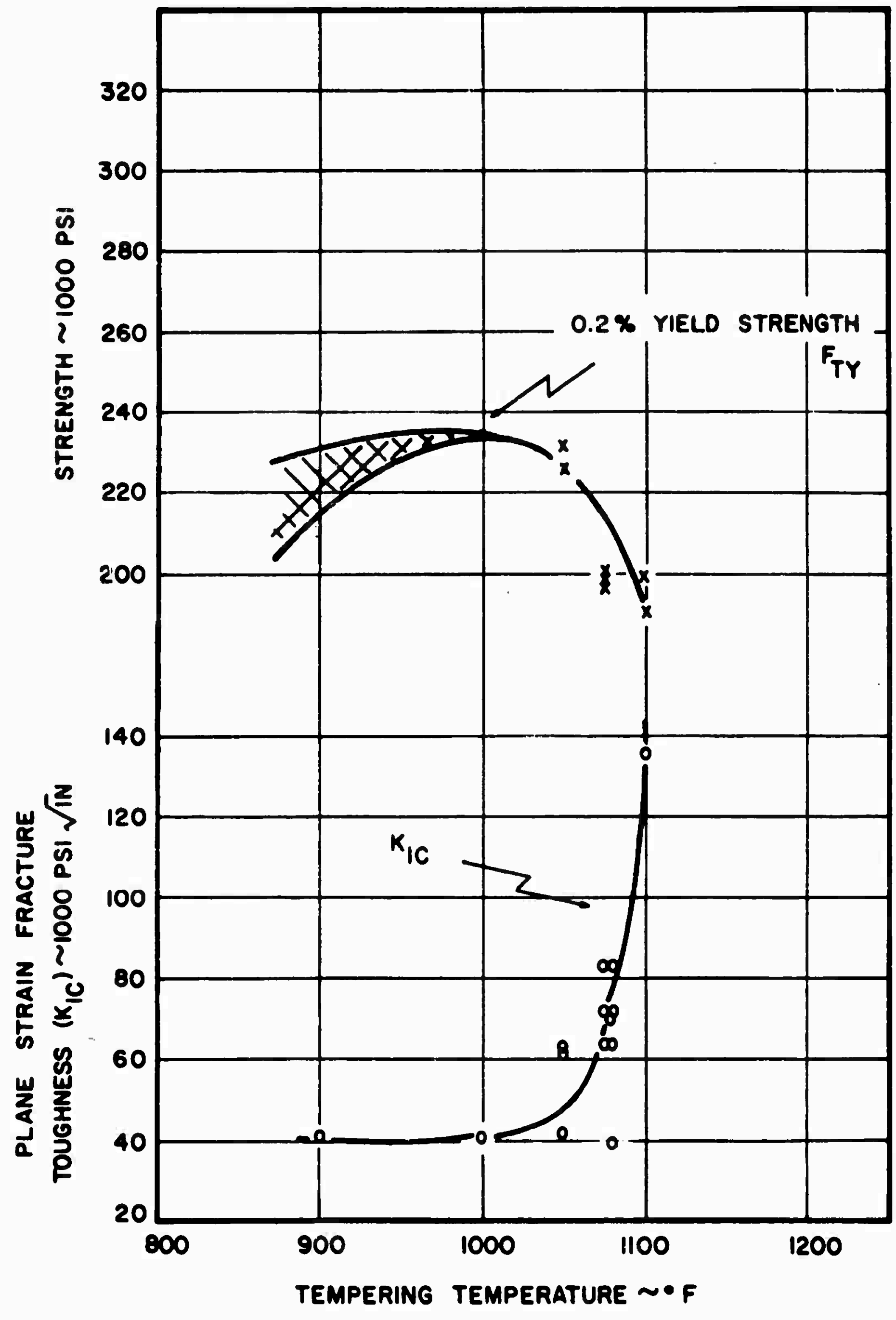

FIG. 7: INFLUENCE OF TEMPERING TEMPERATURE ON THE SMOOTH STRENGTH AND PLANE STRAIN FRACTURE TOUGHNESS OF H-11 DIE STEEL, ROOM TEMPERATURE TESTS. (SEE TABLE 10).

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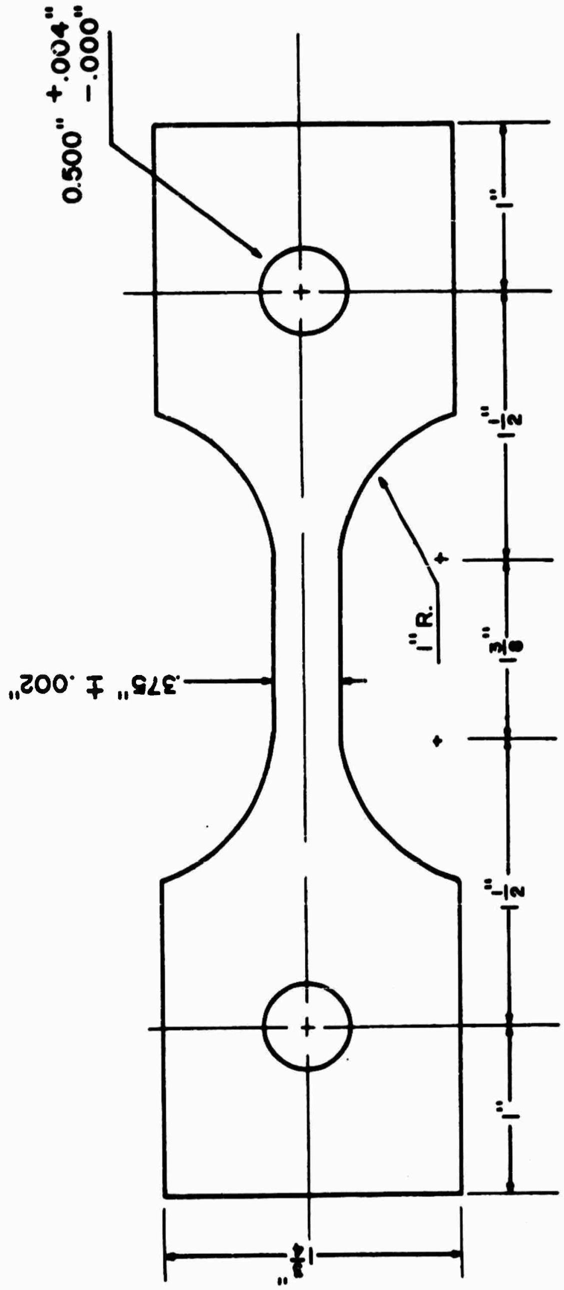

FIG.8: SMOOTH SHEET TENSILE SPECIMEN GEOMETRY.

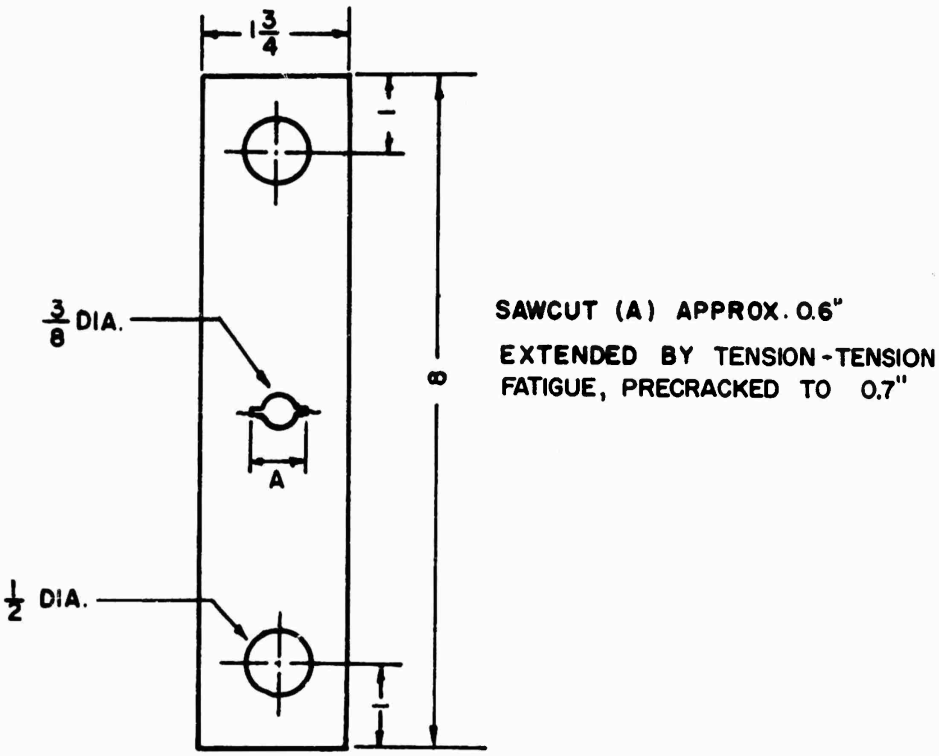

FIG. 9: CENTER PRECRACKED NOTCH TENSILE SPECIMEN

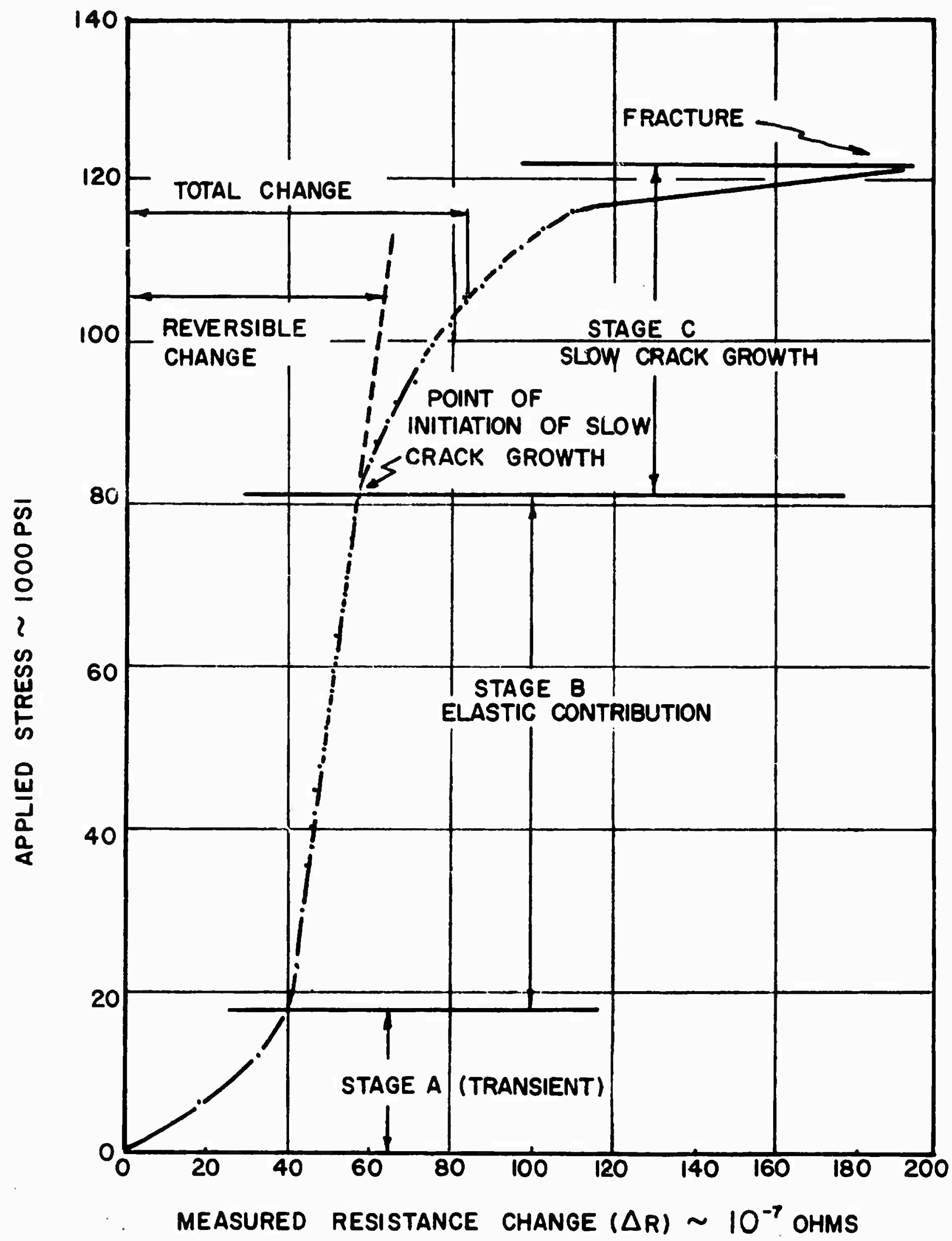

FIG. 10A: RESISTANCE CHANGE AS A FUNCTION OF APPLIED STRESS, 300M STEEL, 290,000 PSI TENSILE STRENGTH, NOTCH TENSILE SPECIMEN, TESTED AT ROOM TEMPERATURE.

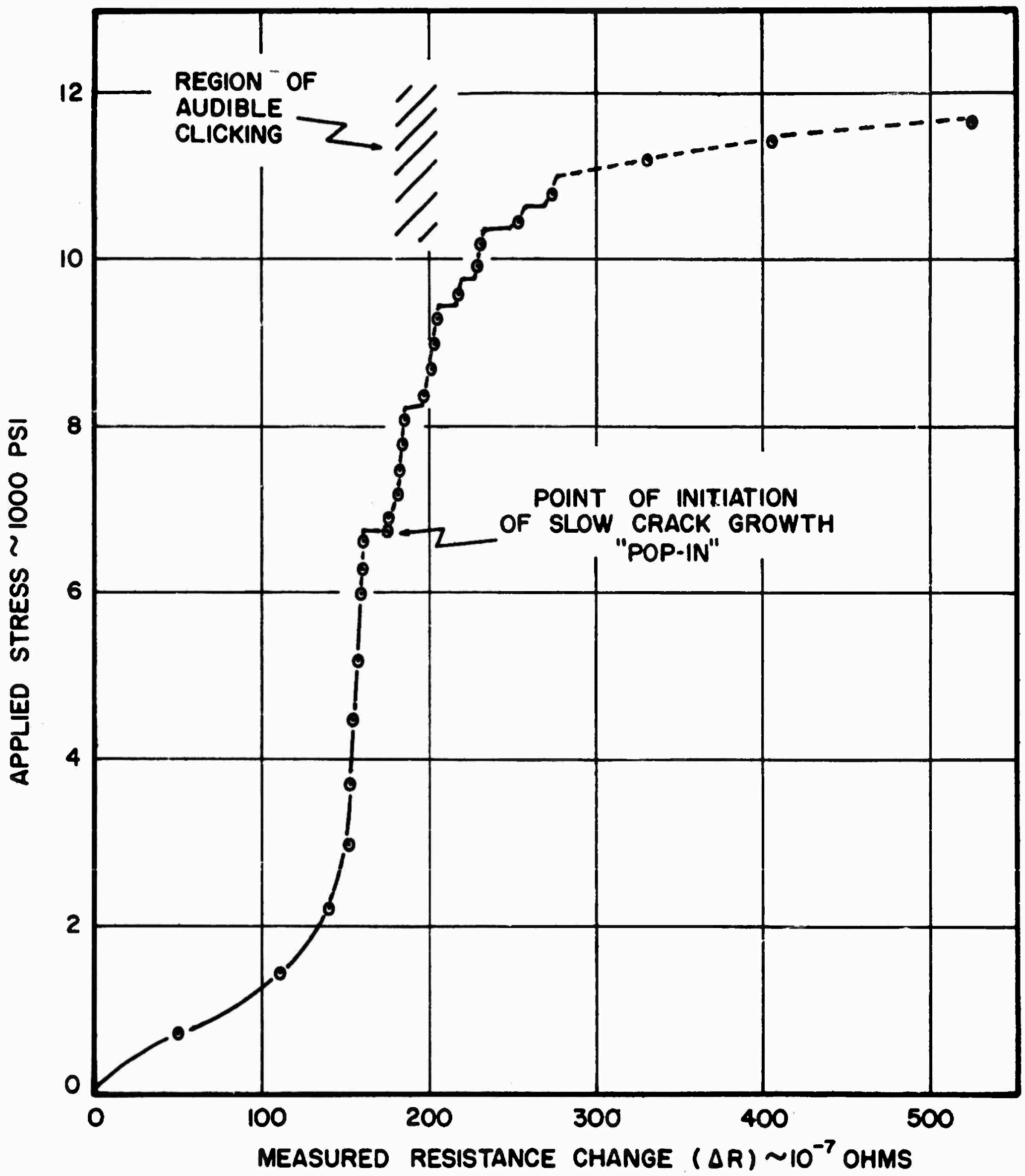

FIG. 10B: RESISTANCE CHANGE AS A FUNCTION OF APPLIED STRESS REVEALING DISCONTINUOUS CRACK GROWTH IN H-11 STEEL, 1000° F TEMPER, TESTED AT 200° F.

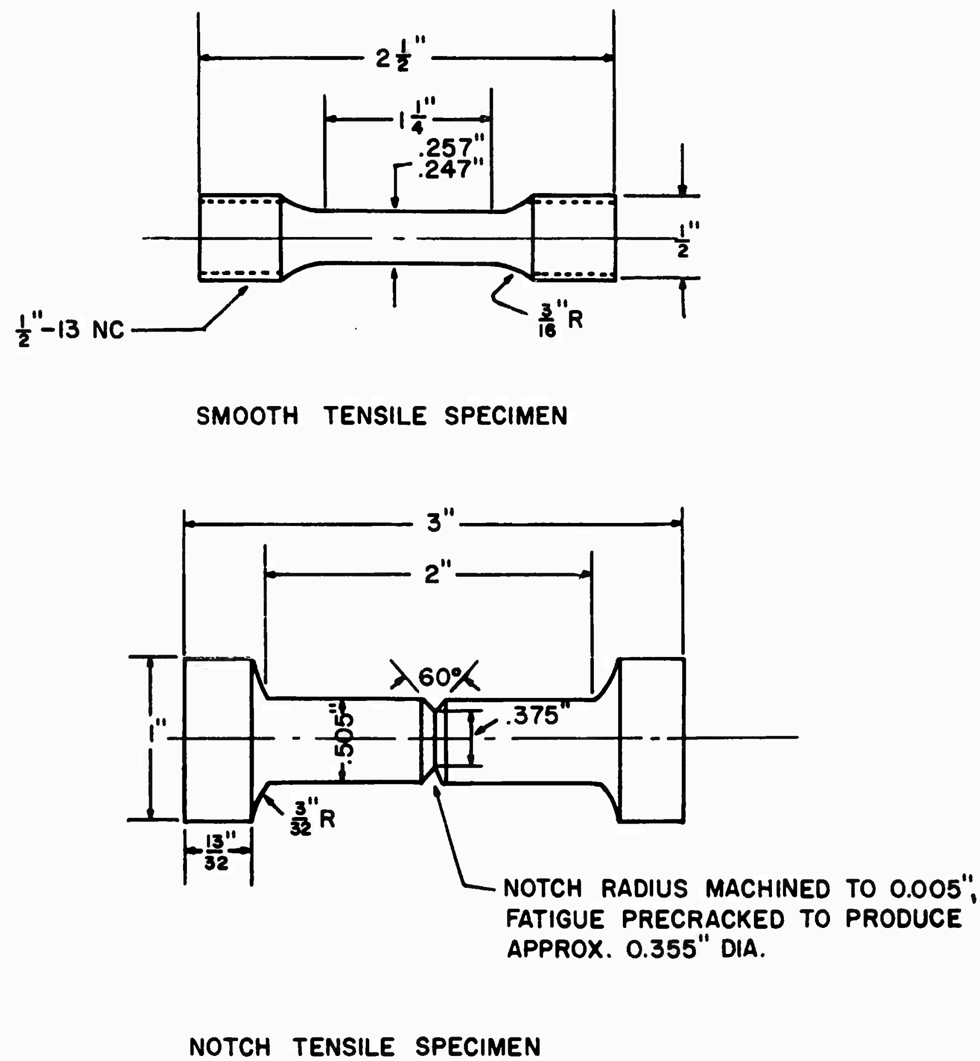

FIG. 11: GEOMETRY OF TEST SPECIMENS FOR BAR STOCK.

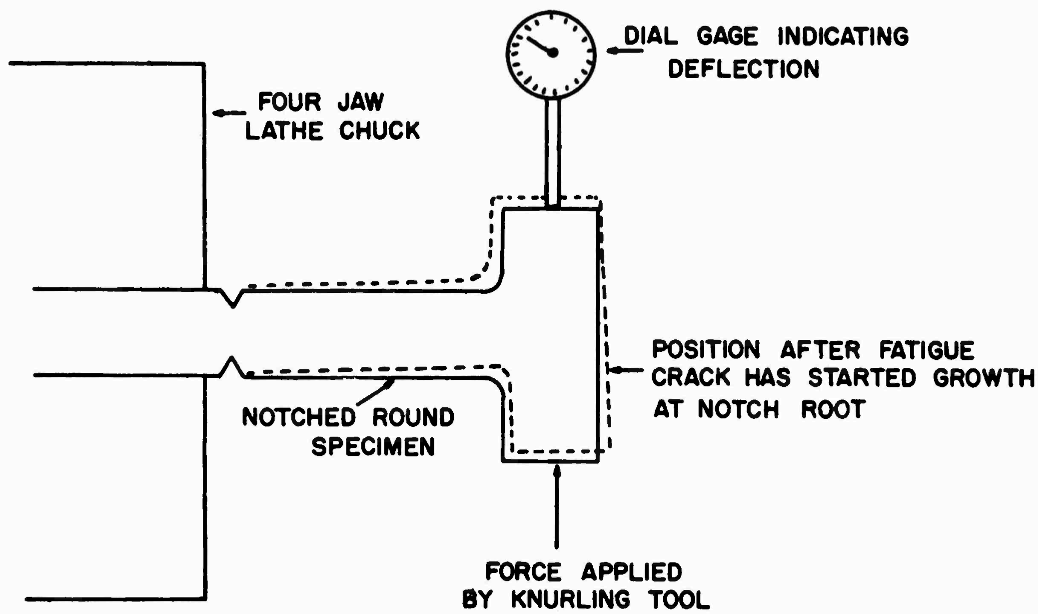

FIG. 12: APPARATUS FOR PRECRACKING ROUND NOTCH SPECIMENS CIRCUMFERENTIALLY BY FATIGUE.

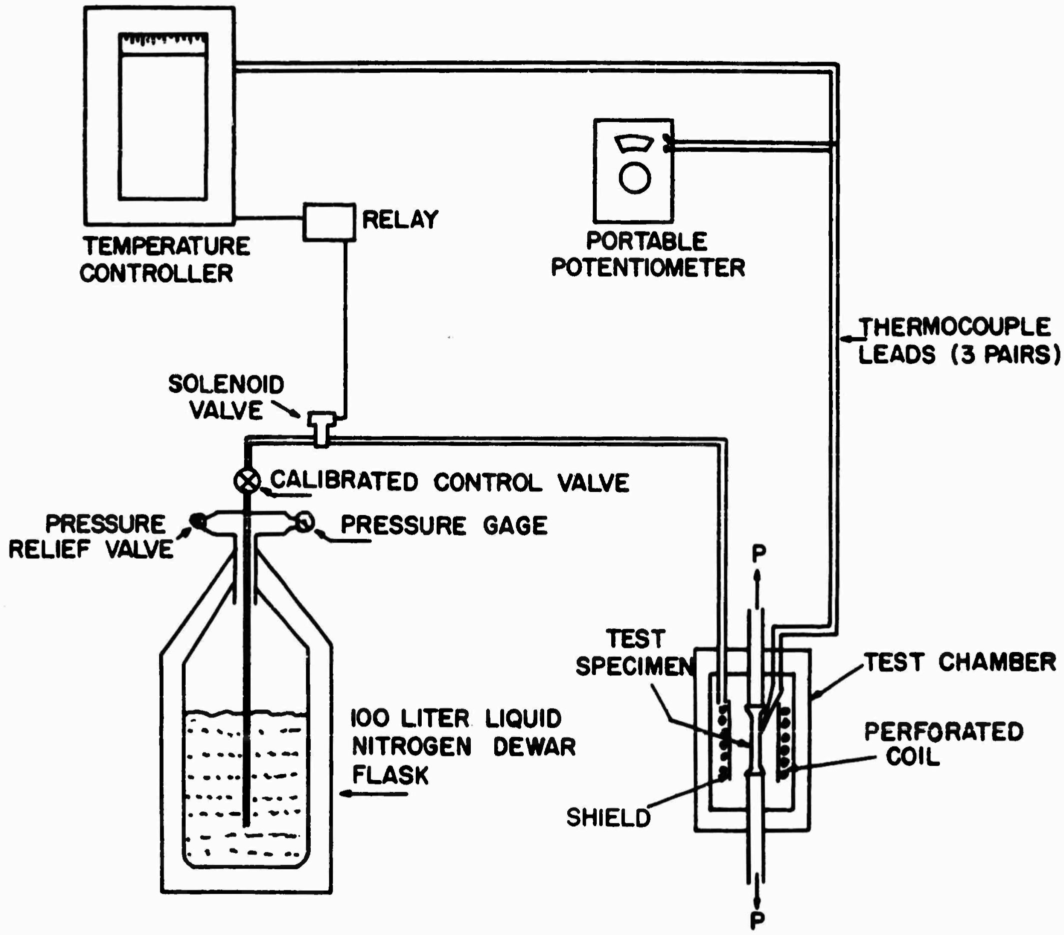

FIG. 13: SCHEMATIC OF APPARATUS FOR MAINTAINING CONSTANT SUBZERO TEMPERATURES.

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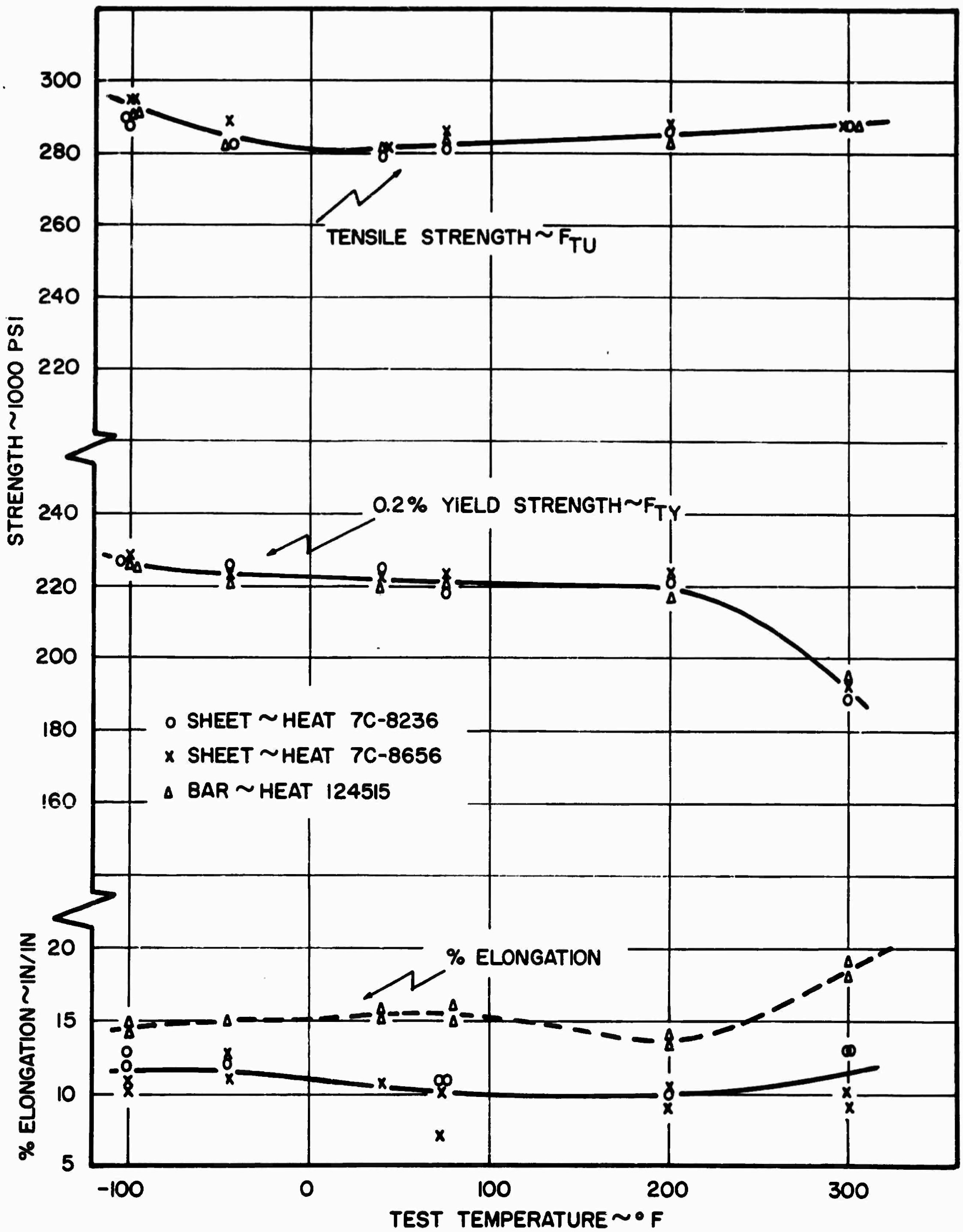

FIG. 14: INFLUENCE OF TEMPERATURE ON THE SMOOTH TENSILE PROPERTIES OF 4340 STEEL, TEMPERED AT 400°F, LONGITUDINAL DIRECTION.

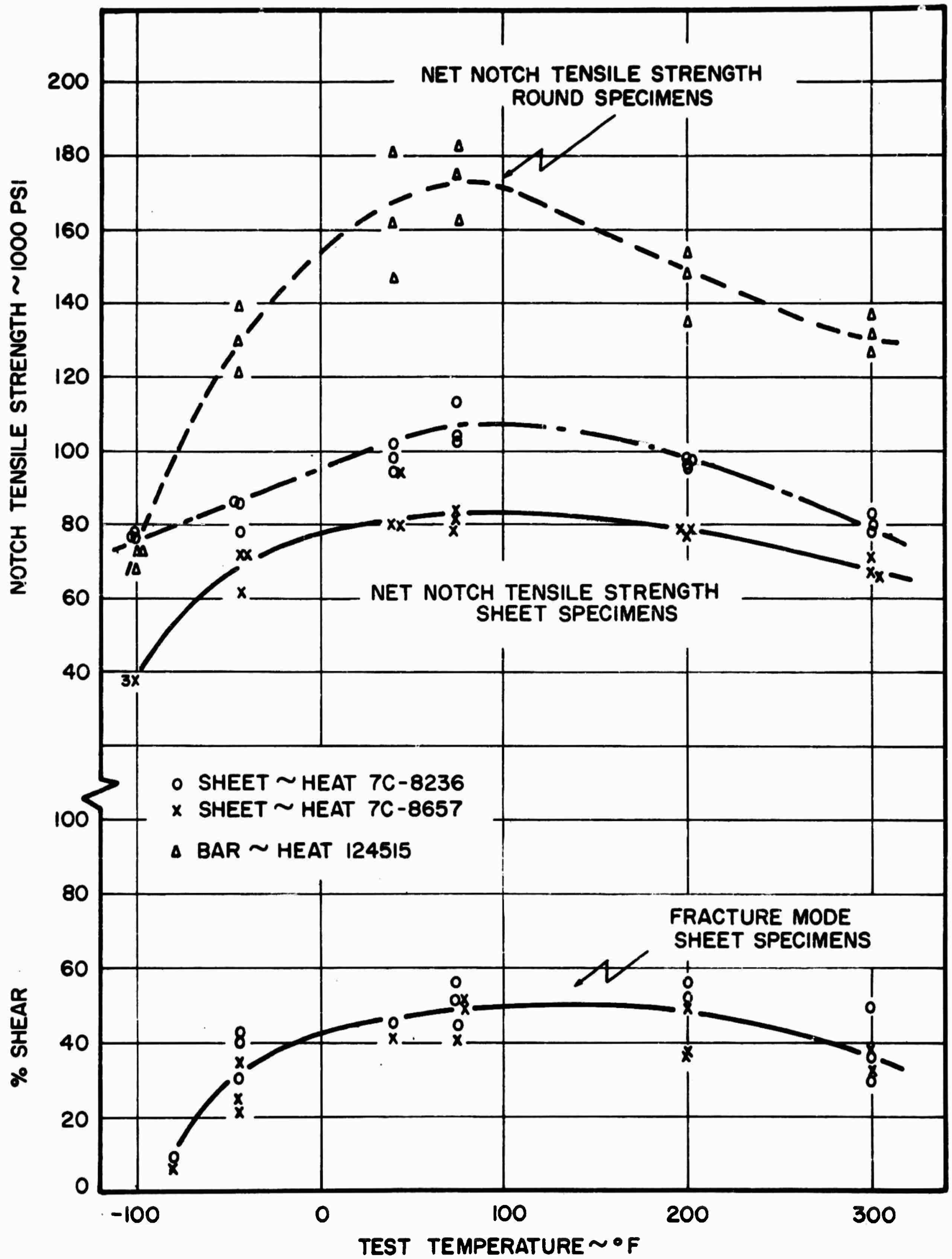

FIG. 15: INFLUENCE OF TEMPERATURE ON NOTCH TENSILE PROPERTIES OF 4340 STEEL, TEMPERED AT 400°F, LONGITUDINAL DIRECTION.

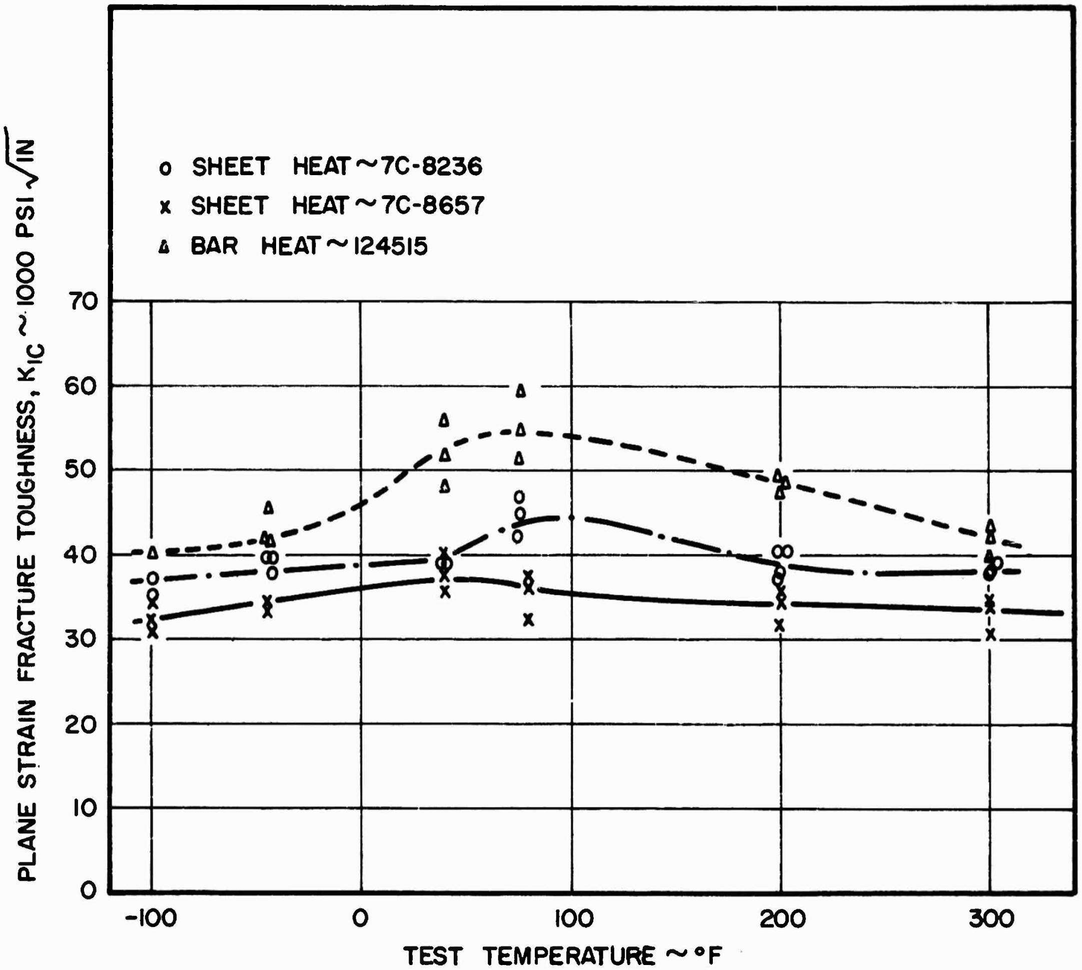

FIG. 16: INFLUENCE OF TEMPERATURE ON THE PLANE STRAIN FRACTURE TOUGHNESS OF 4340 STEEL, TEMPERED AT 400° F, LONGITUDINAL DIRECTION.

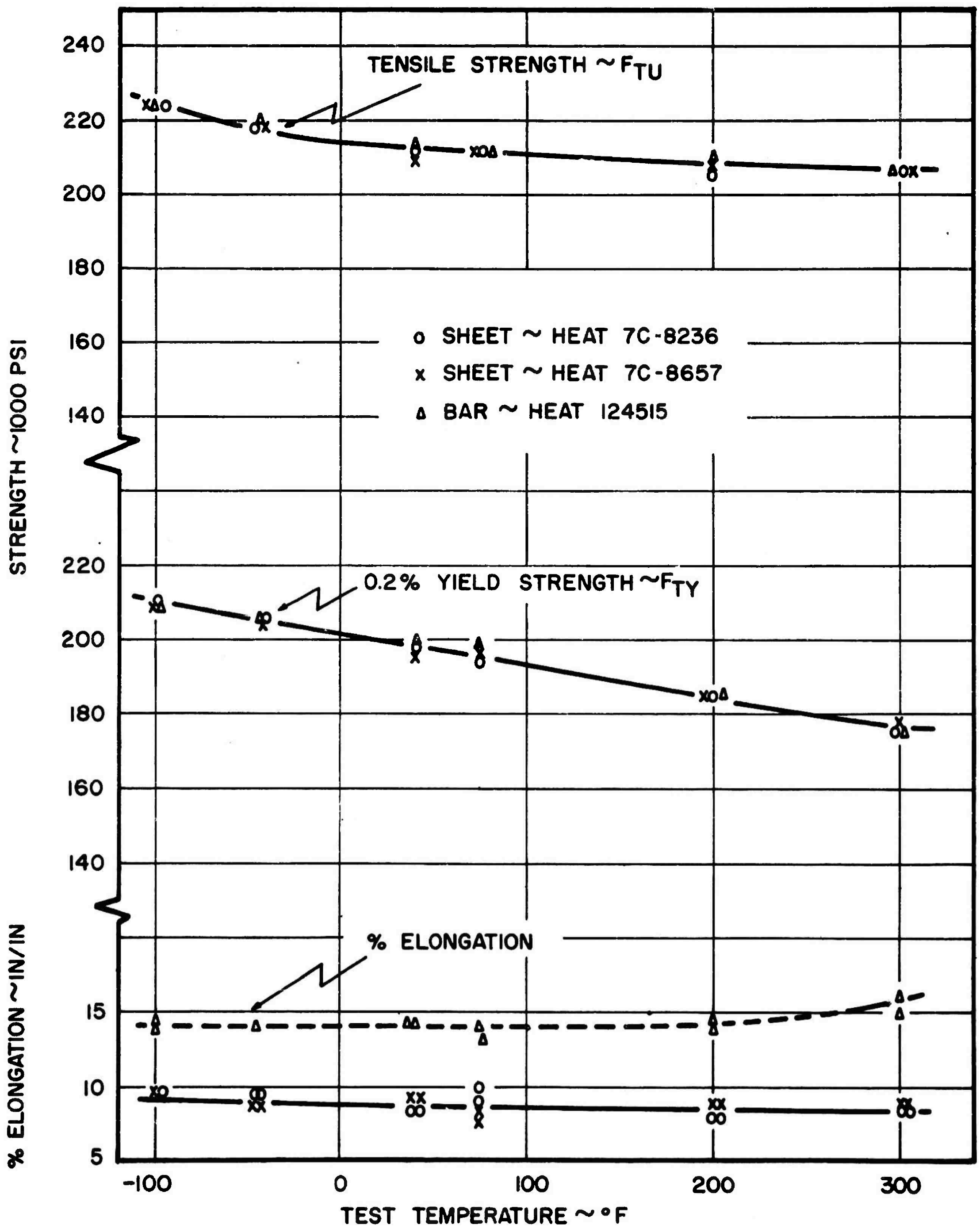

FIG. 17: INFLUENCE OF TEMPERATURE ON THE SMOOTH TENSILE PROPERTIES OF 4340 STEEL, TEMPERED AT 750° F, LONGITUDINAL DIRECTION.

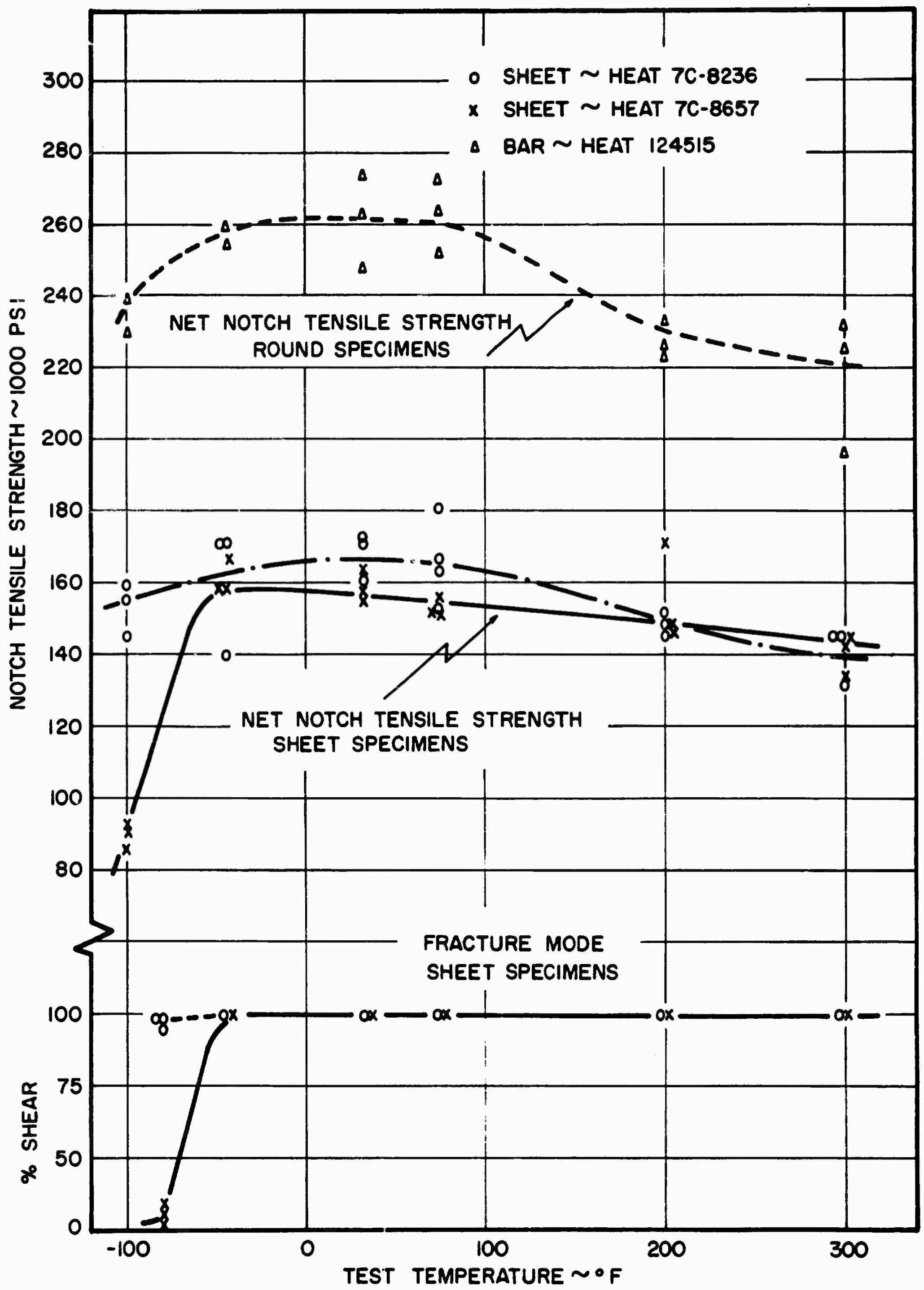

FIG. 18: INFLUENCE OF TEMPERATURE ON NOTCH TENSILE PROPERTIES OF 4340 STEEL, TEMPERED AT 750° F, LONGITUDINAL DIRECTION.

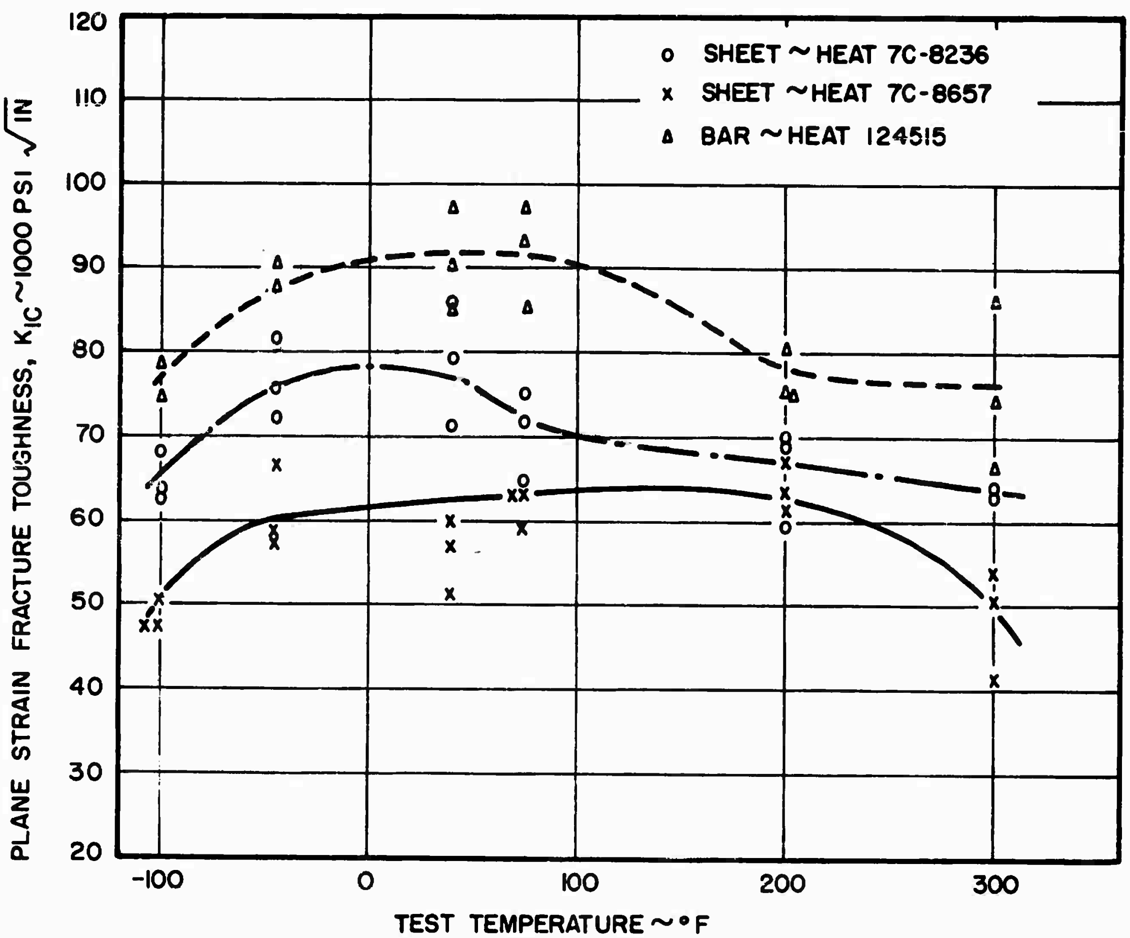

FIG. 19: INFLUENCE OF TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF 4340 STEEL, TEMPERED AT 750°F, LONGITUDINAL DIRECTION.

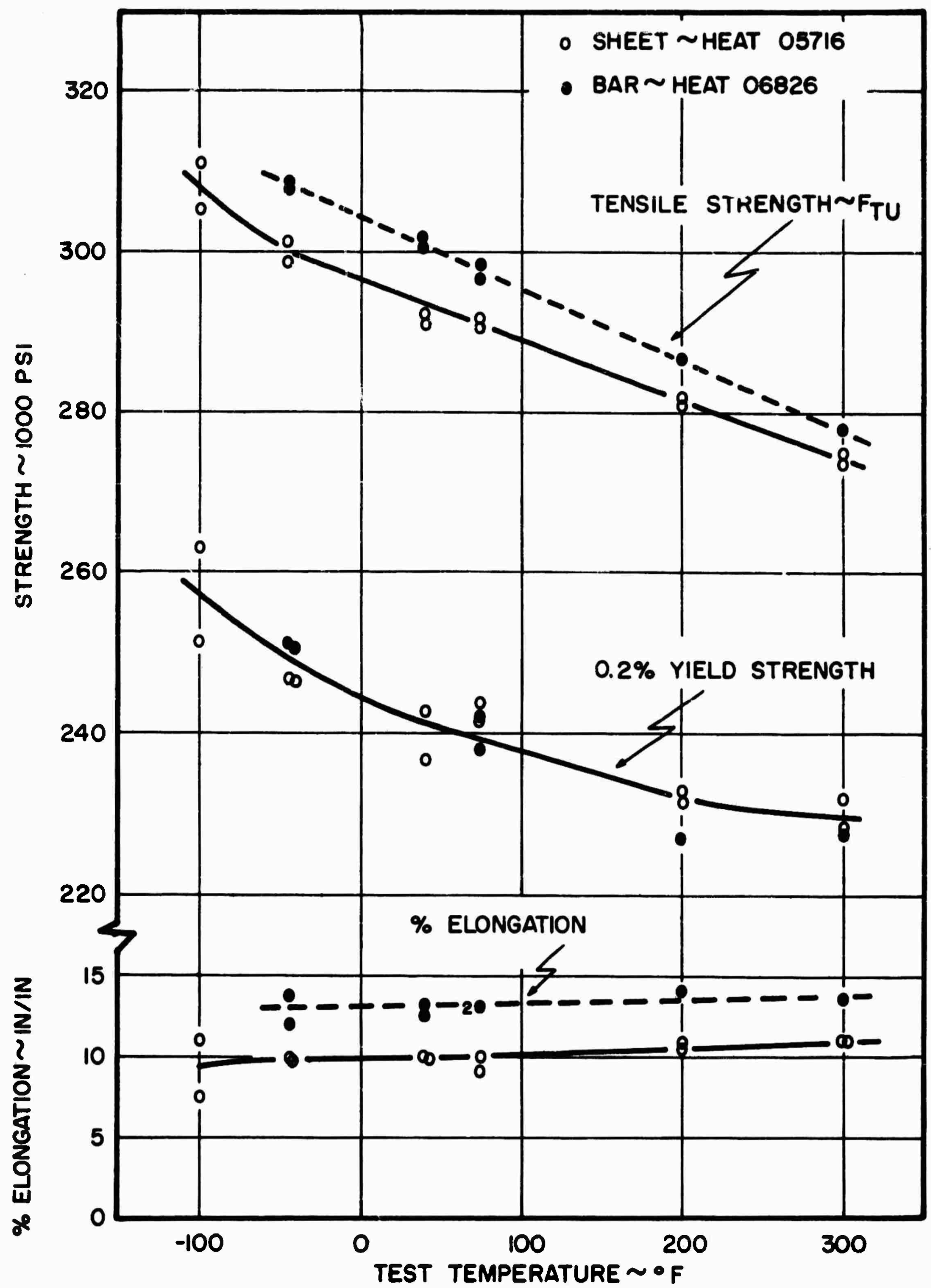

FIG. 20: INFLUENCE OF TEMPERATURE ON THE SMOOTH TENSILE PROPERTIES OF H-11 STEEL, TEMPERED AT 1000° F, LONGITUDINAL DIRECTION.

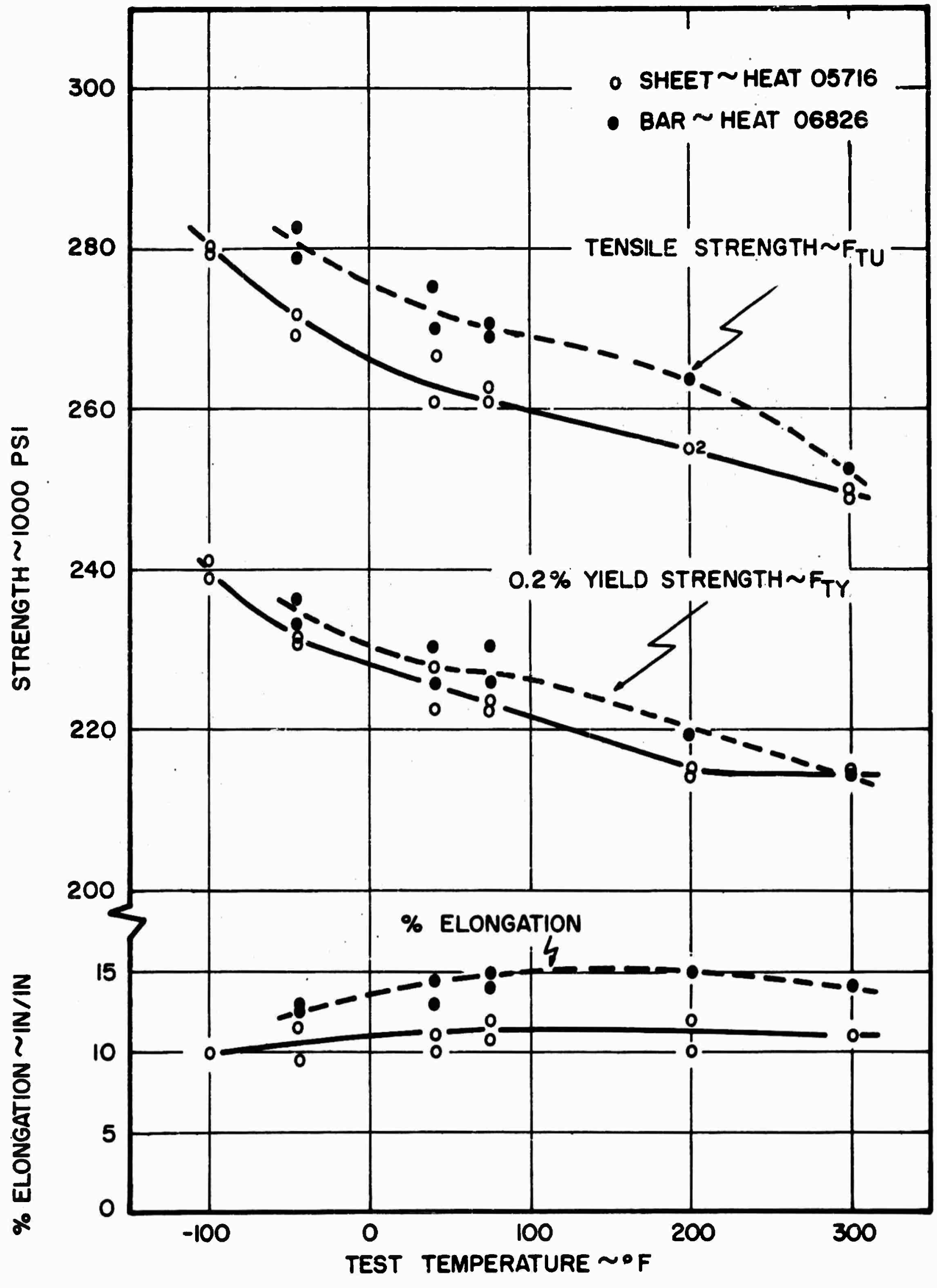

FIG. 21: INFLUENCE OF TEMPERATURE ON SMOOTH TENSILE PROPERTIES OF H-11 STEEL, TEMPERED AT 1050° F, LONGITUDINAL DIRECTION.

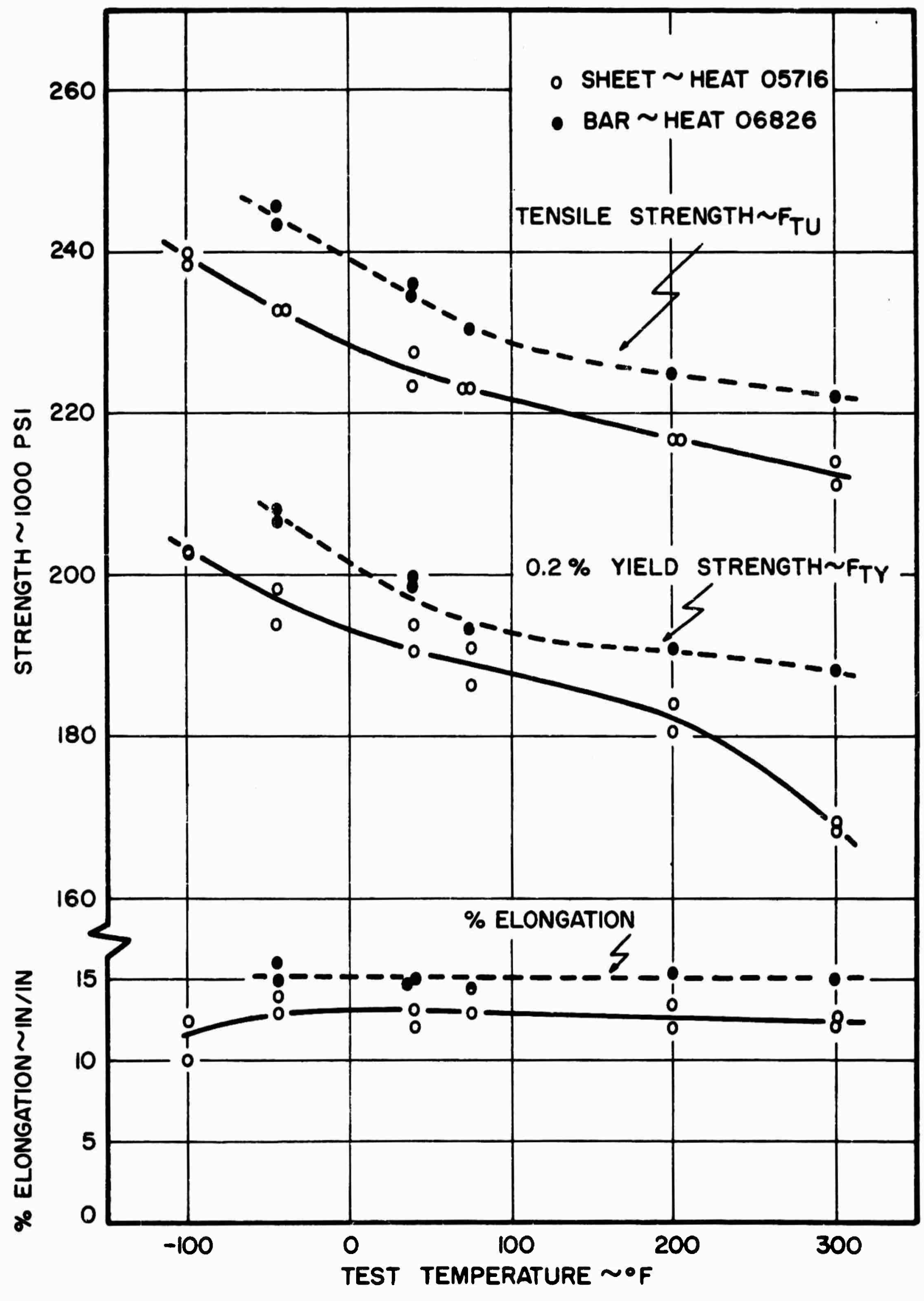

FIG. 22: INFLUENCE OF TEMPERATURE ON SMOOTH TENSILE PROPERTIES OF H-11 STEEL, TEMPERED AT 1100° F, LONGITUDINAL DIRECTION

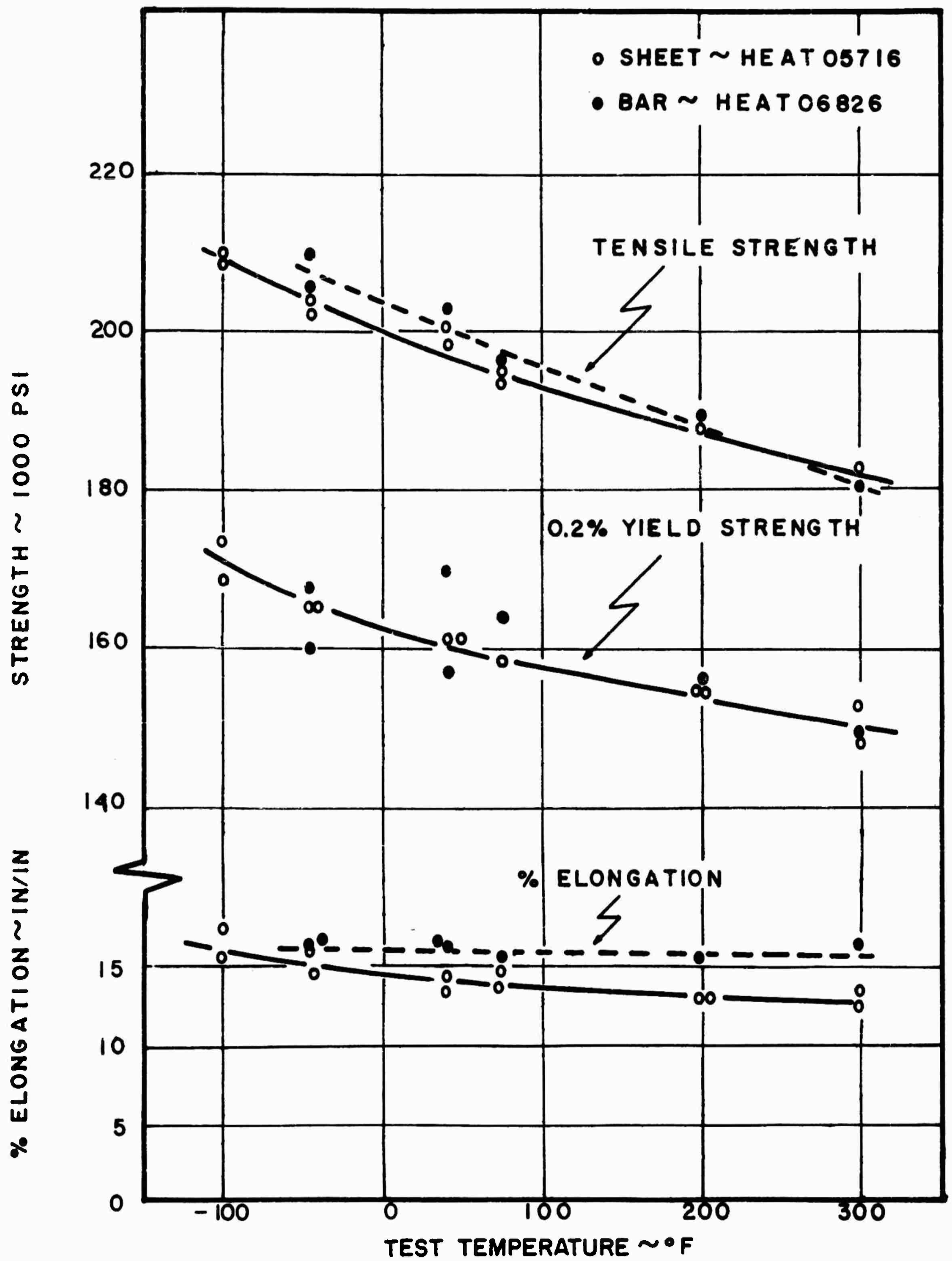

FIG 23: INFLUENCE OF TEMPERATURE ON SMOOTH TENSILE PROPERTIES OF H-11 STEEL, TEMPERED AT 1150 °F, LONGITUDINAL DIRECTION.

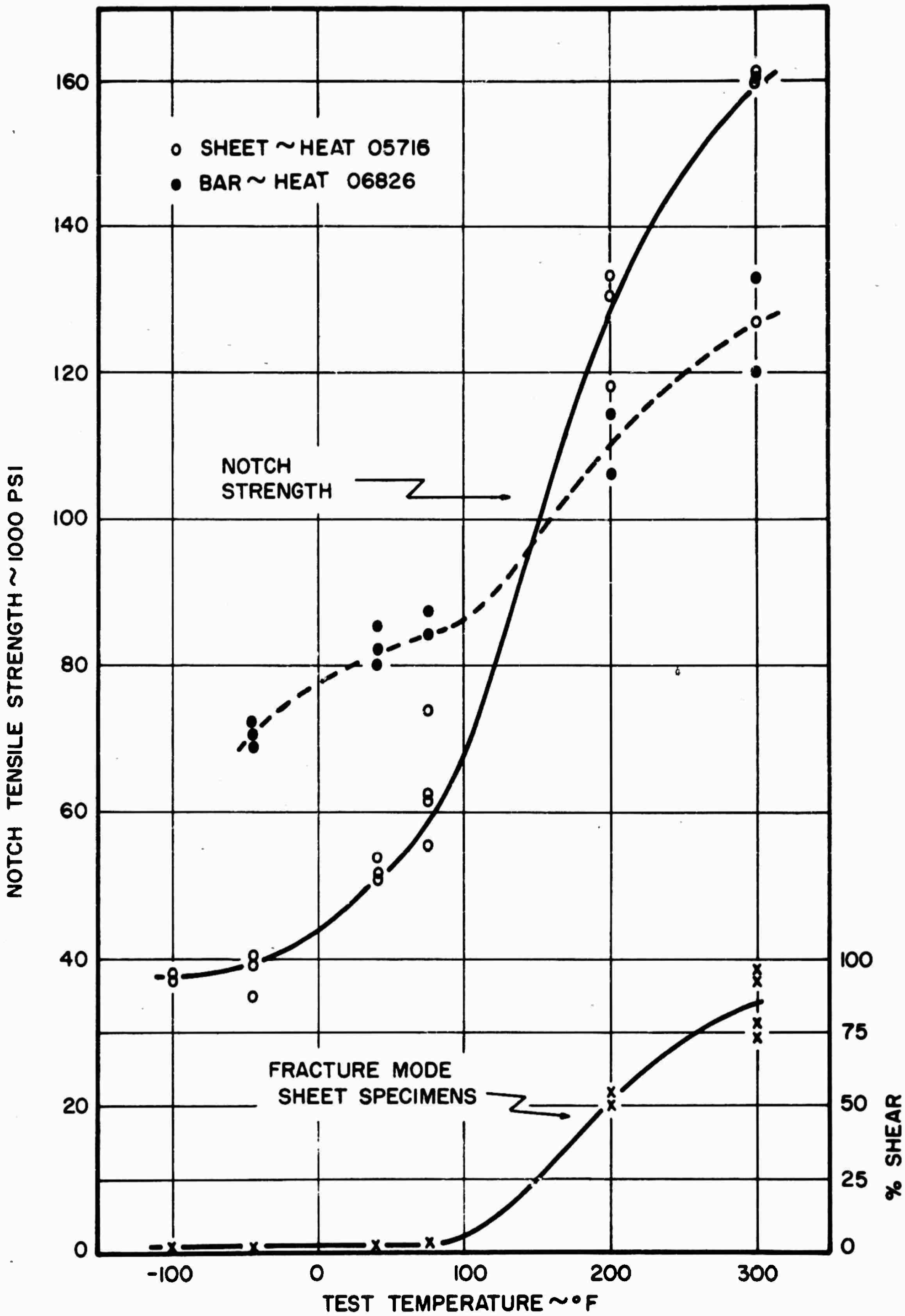

FIG. 24: INFLUENCE OF TEMPERATURE ON NOTCH TENSILE PROPERTIES OF H-11 STEEL, TEMPERED AT 1000° F, LONGITUDINAL DIRECTION.

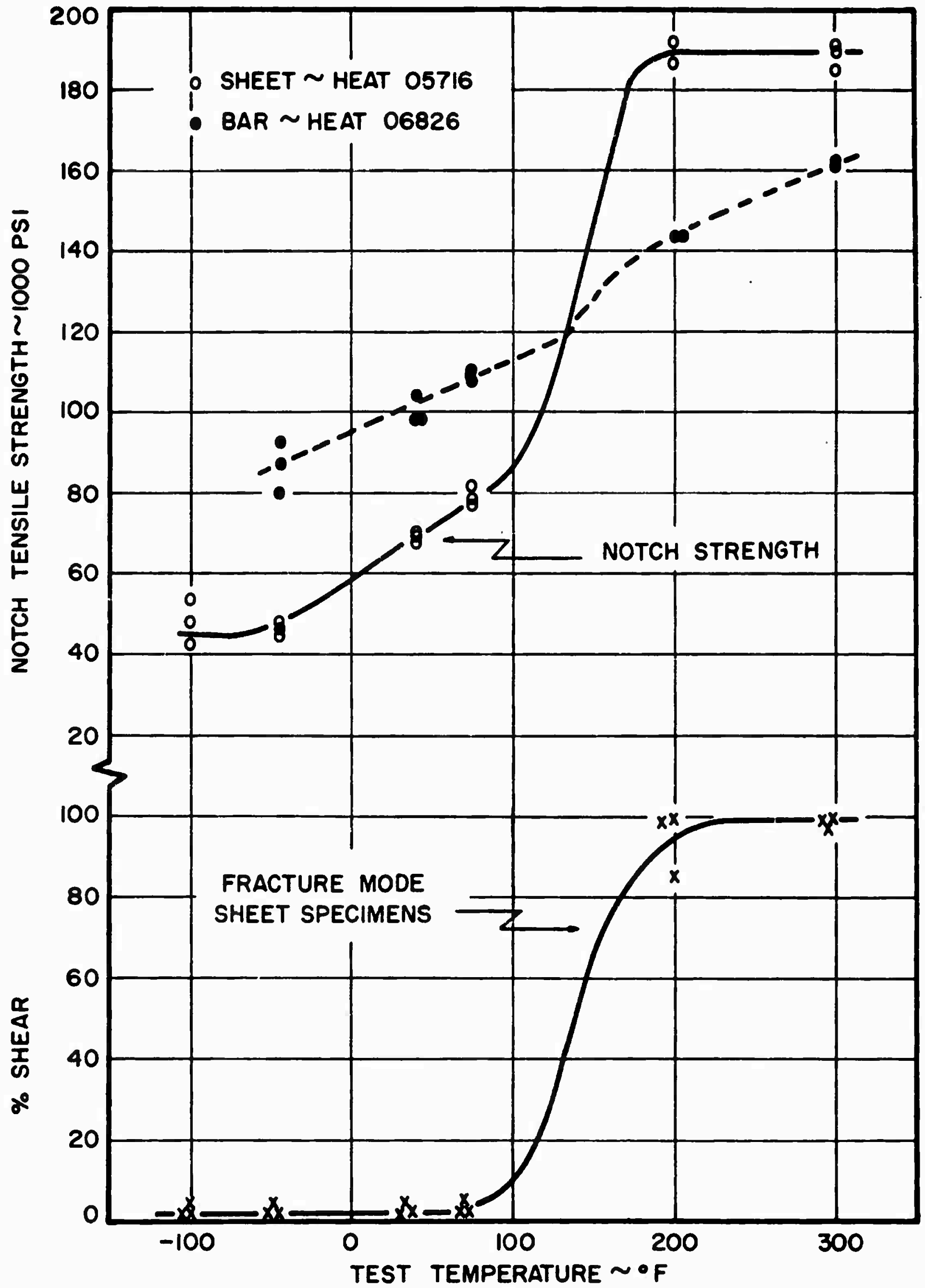

FIG. 25: INFLUENCE OF TEMPERATURE ON NOTCH TENSILE PROPERTIES OF H-11 STEEL, TEMPERED AT 1050° F, LONGITUDINAL DIRECTION.

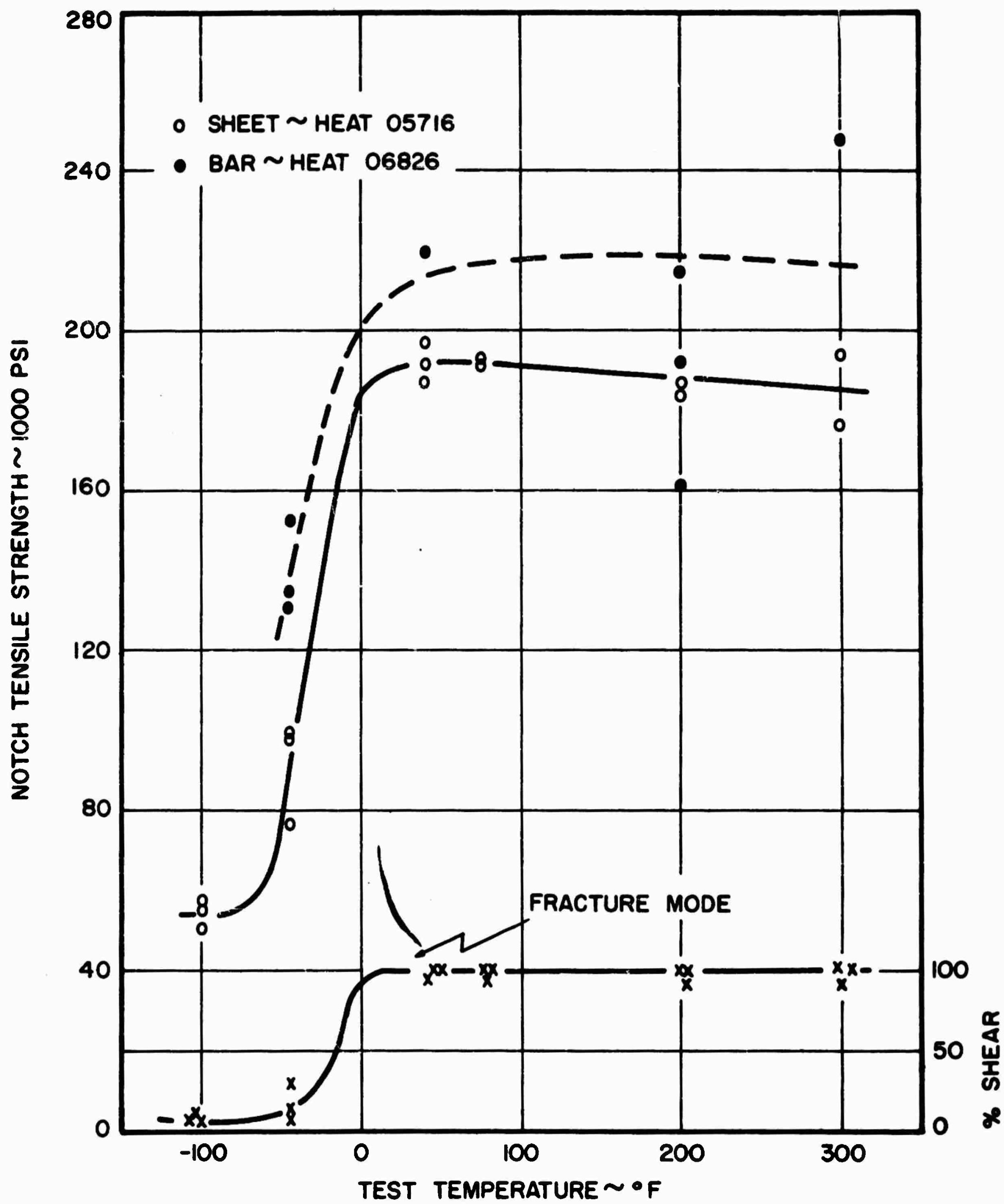

FIG. 26: INFLUENCE OF TEMPERATURE ON NOTCH TENSILE PROPERTIES OF H-11 STEEL, 1100° F TEMPER, LONGITUDINAL DIRECTION.

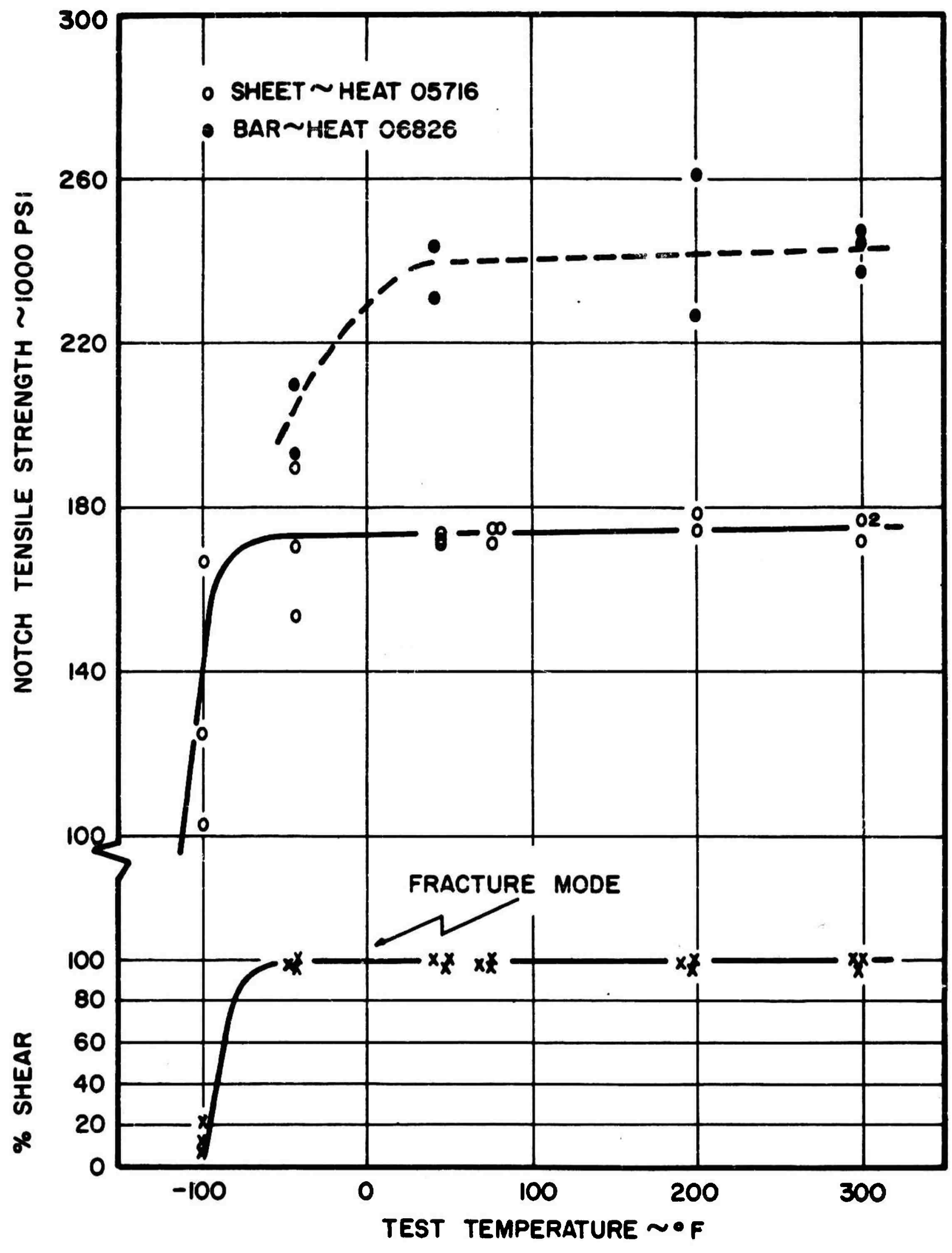

FIG. 27: INFLUENCE OF TEMPERATURE ON NOTCH TENSILE PROPERTIES OF H-11 STEEL, TEMPERED AT 1150° F, LONGITUDINAL DIRECTION.

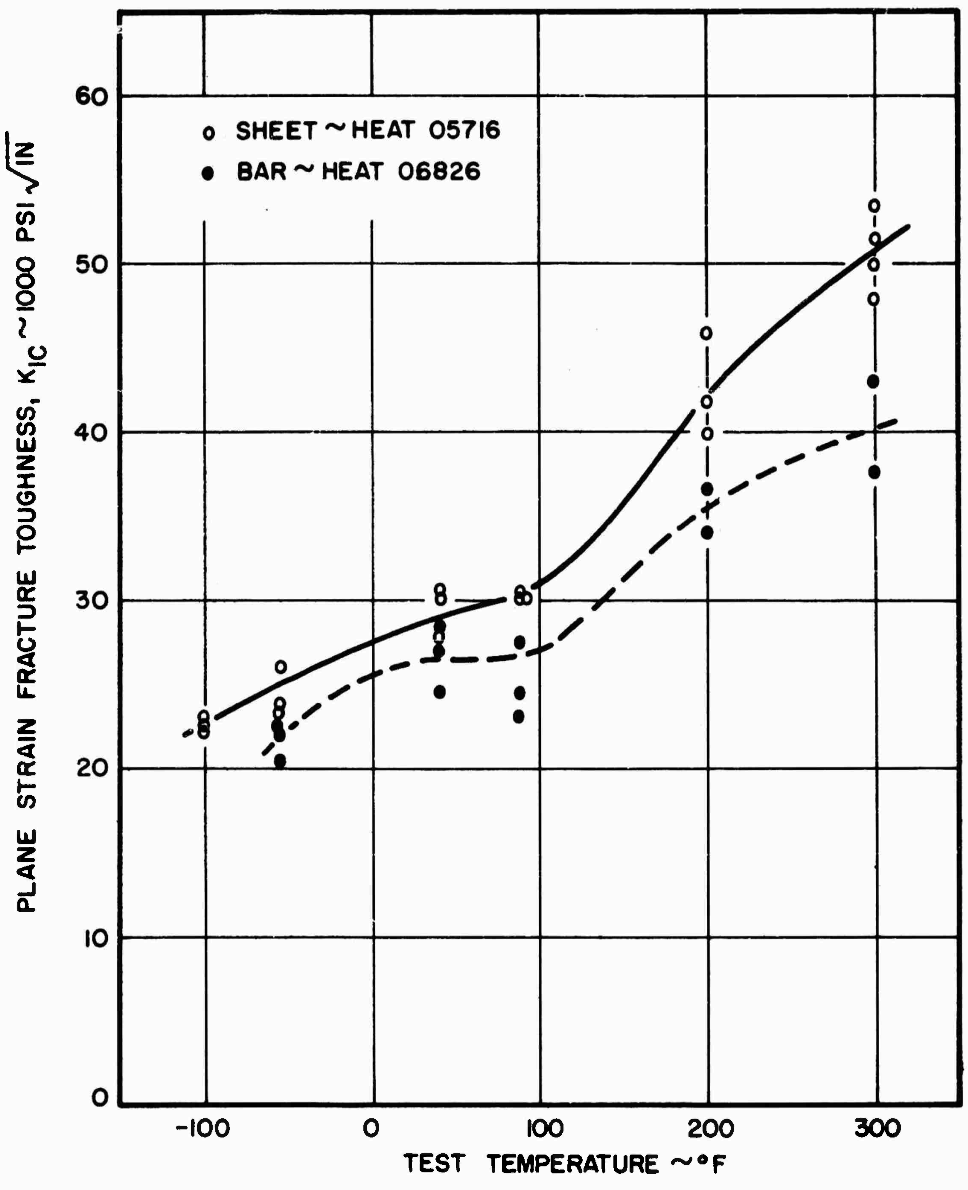

FIG.28: INFLUENCE OF TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF H-11 STEEL, TEMPERED AT 1000°F, LONGITUDINAL DIRECTION.

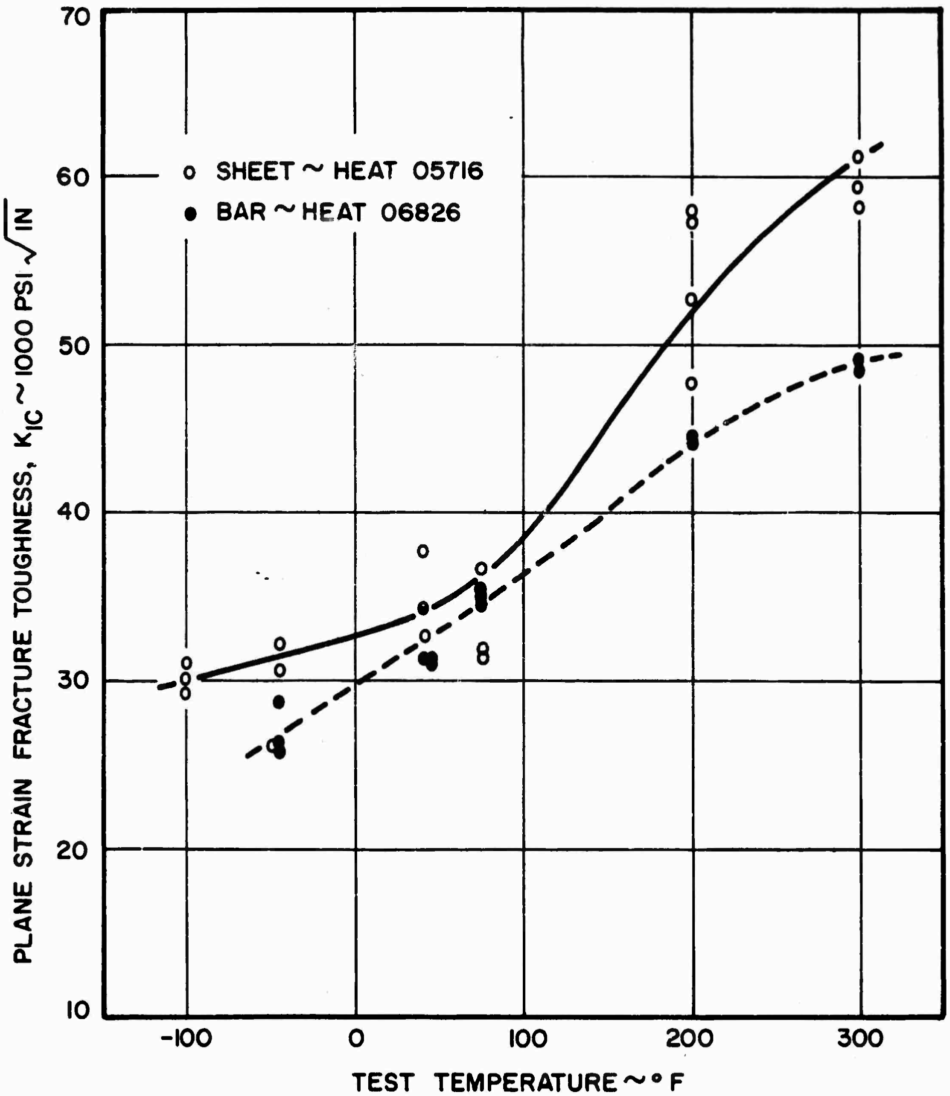

FIG. 29: INFLUENCE OF TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF H-11 STEEL, TEMPERED AT 1050°F, LONGITUDINAL DIRECTION.

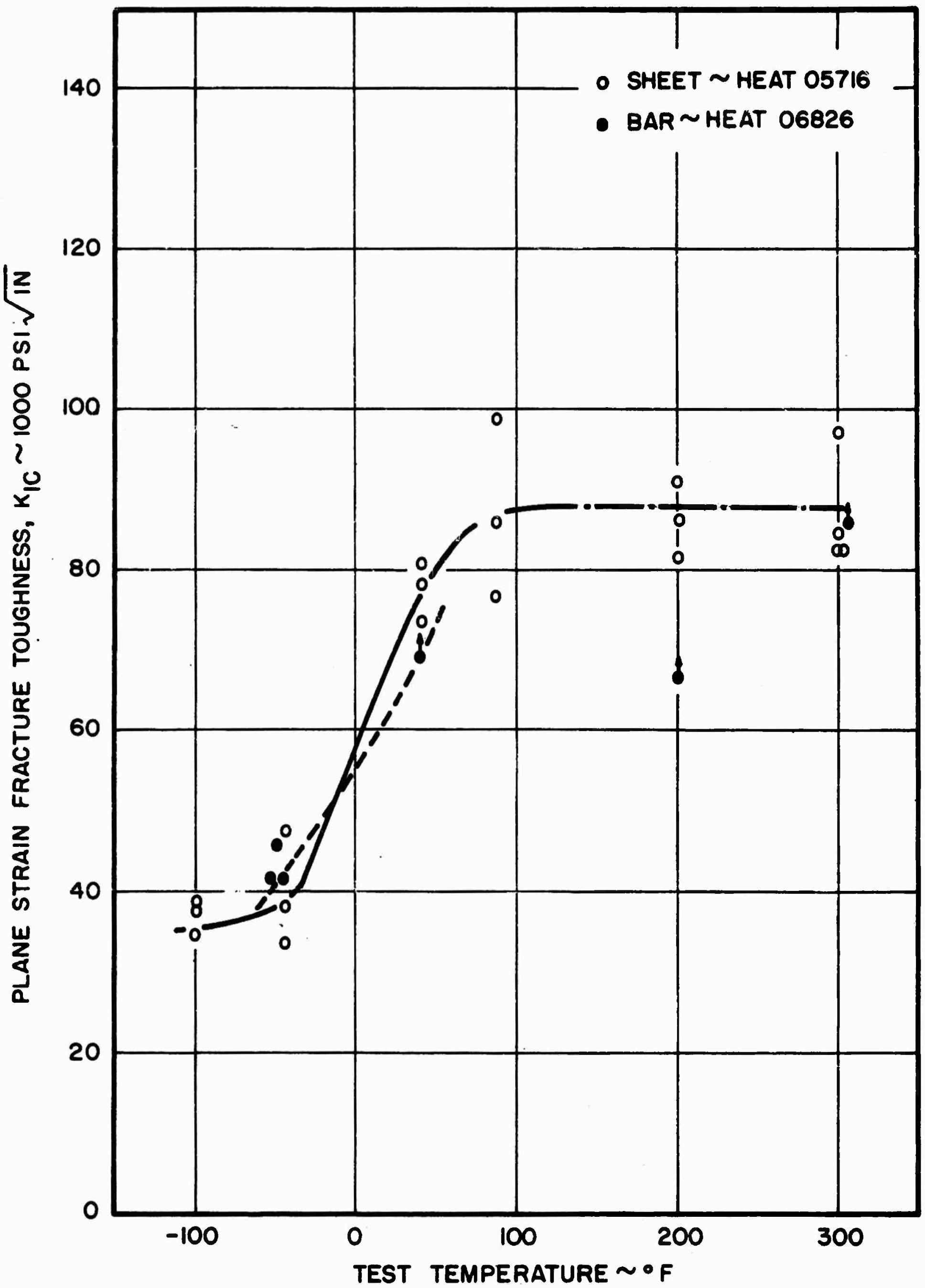

FIG. 30: INFLUENCE OF TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF H-11 STEEL, TEMPERED AT 1100° F, LONGITUDINAL DIRECTION.

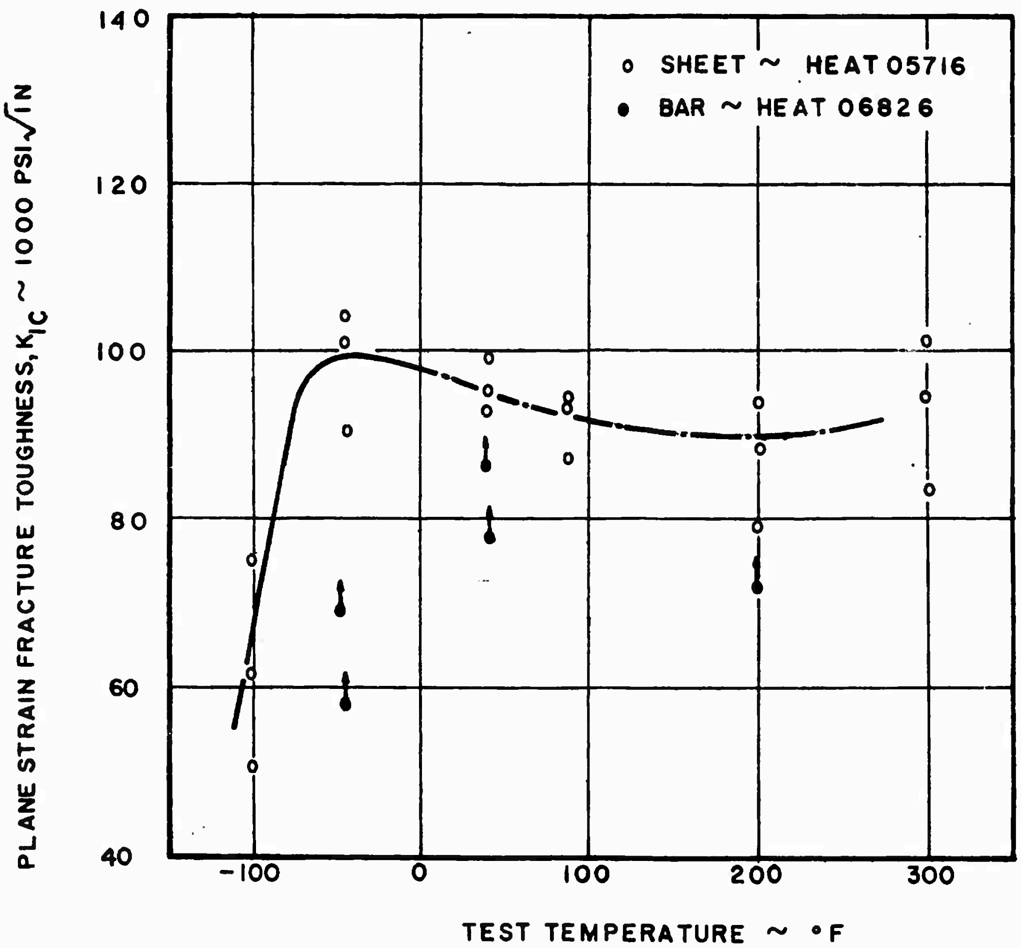

FIG. 31: INFLUENCE OF TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF H-11 STEEL, TEMPERED AT 1150 °F, LONGITUDINAL DIRECTION

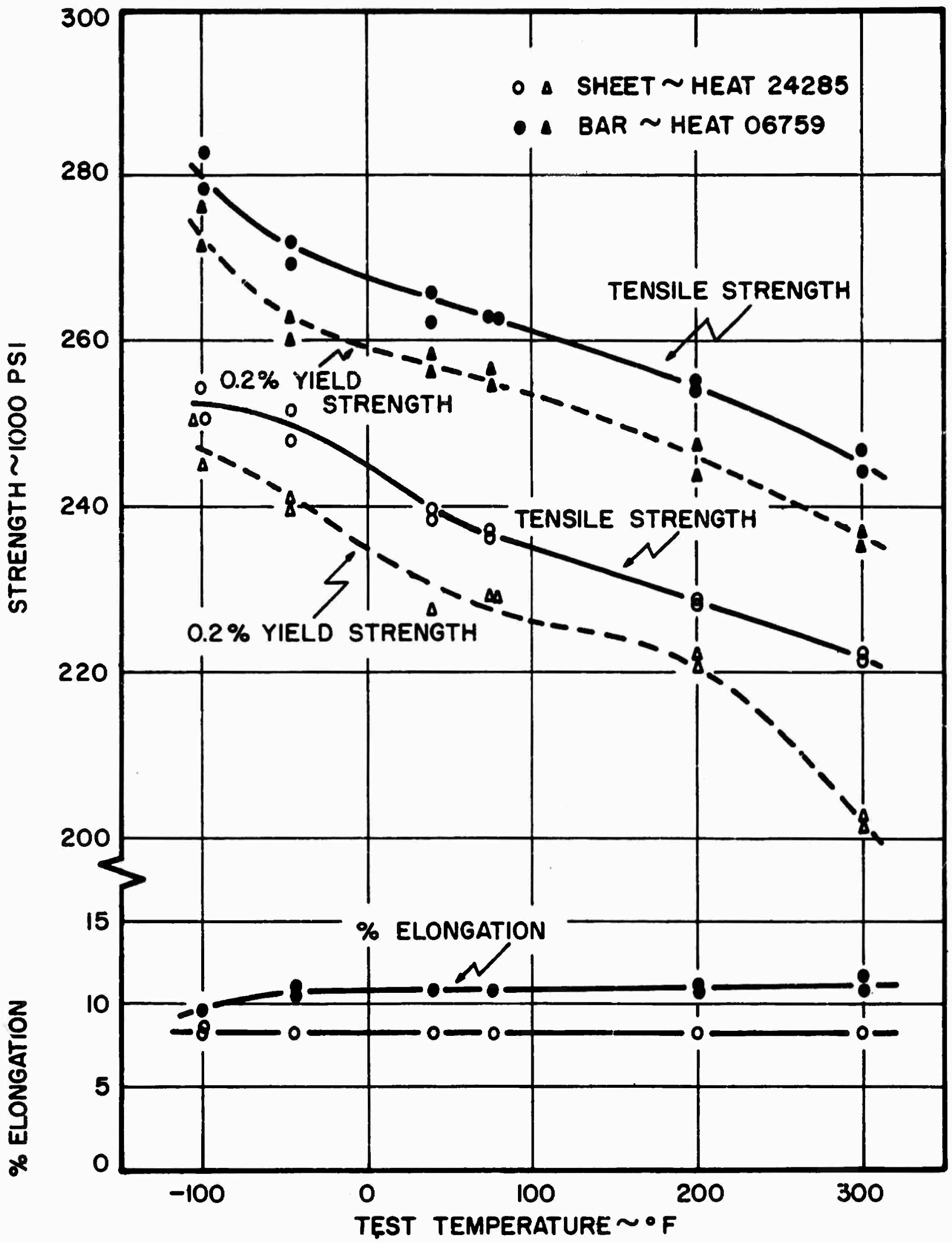

FIG. 32: INFLUENCE OF TEMPERATURE ON TENSILE PROPERTIES OF 18-5-7 MARAGING STEEL, LONGITUDINAL DIRECTION.

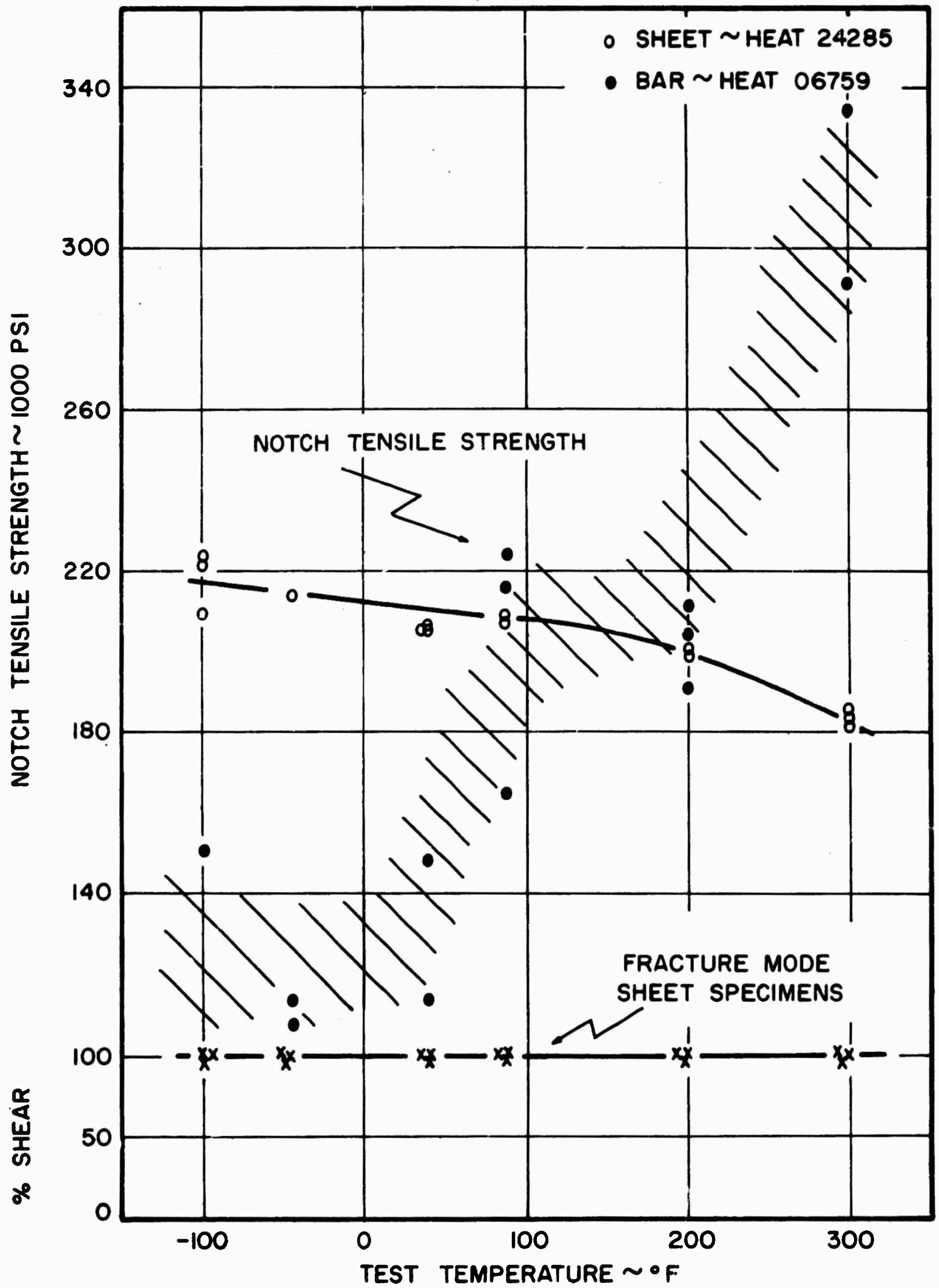

FIG. 33: INFLUENCE OF TEMPERATURE ON NOTCH TENSILE PROPERTIES OF 18-5-7 MARAGING STEEL, LONGITUDINAL DIRECTION.

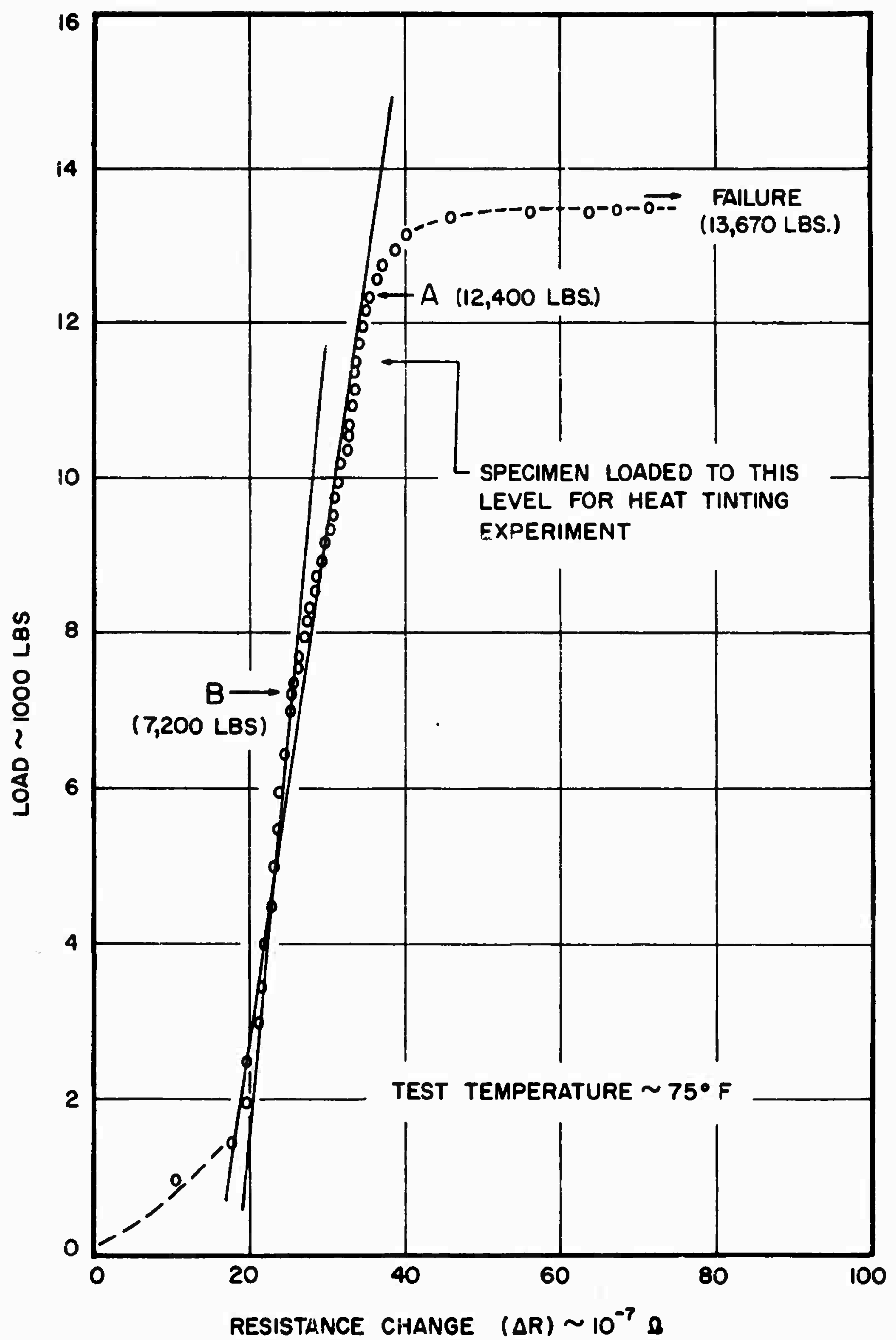

FIG. 34: TYPICAL LOAD-RESISTANCE CURVE FOR MARAGING STEEL ILLUSTRATING THE TWO DIFFERENT K_{IC} VALUES WHICH CAN BE OBTAINED.

50 X 7483

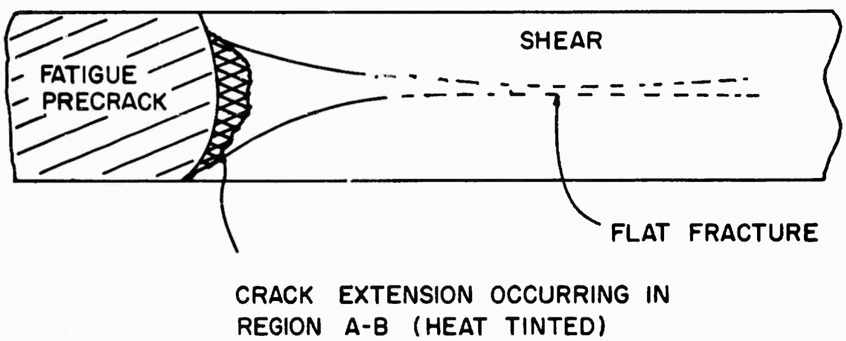

FIG. 35: PHOTOGRAPH OF SPECIMEN SHOWING SLIGHT AMOUNT OF SLOW CRACK GROWTH WHICH OCCURS IN MARAGING STEELS.

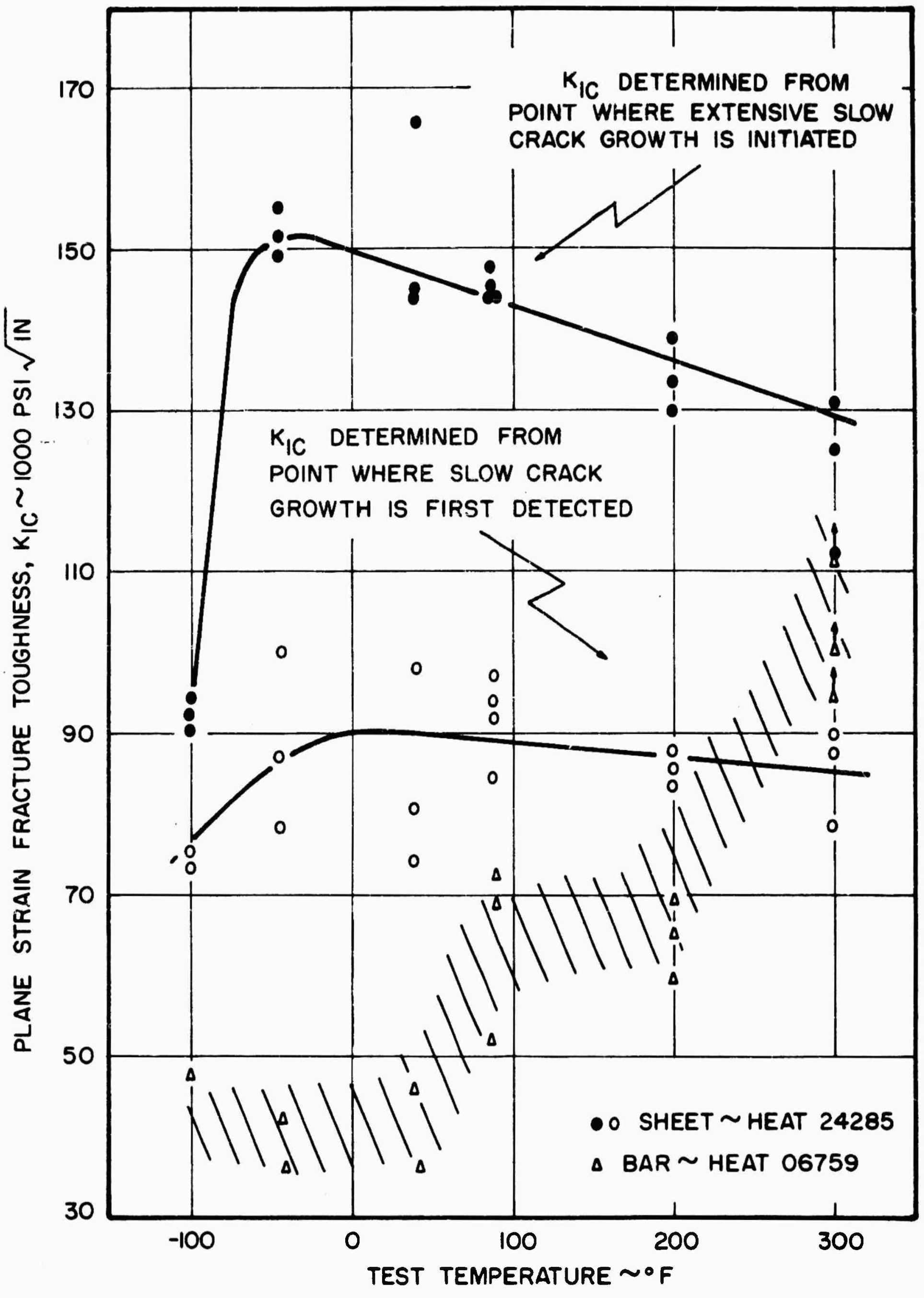

FIG. 36: INFLUENCE OF TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF 18-5-7 MARAGING STEEL, LONGITUDINAL DIRECTION.

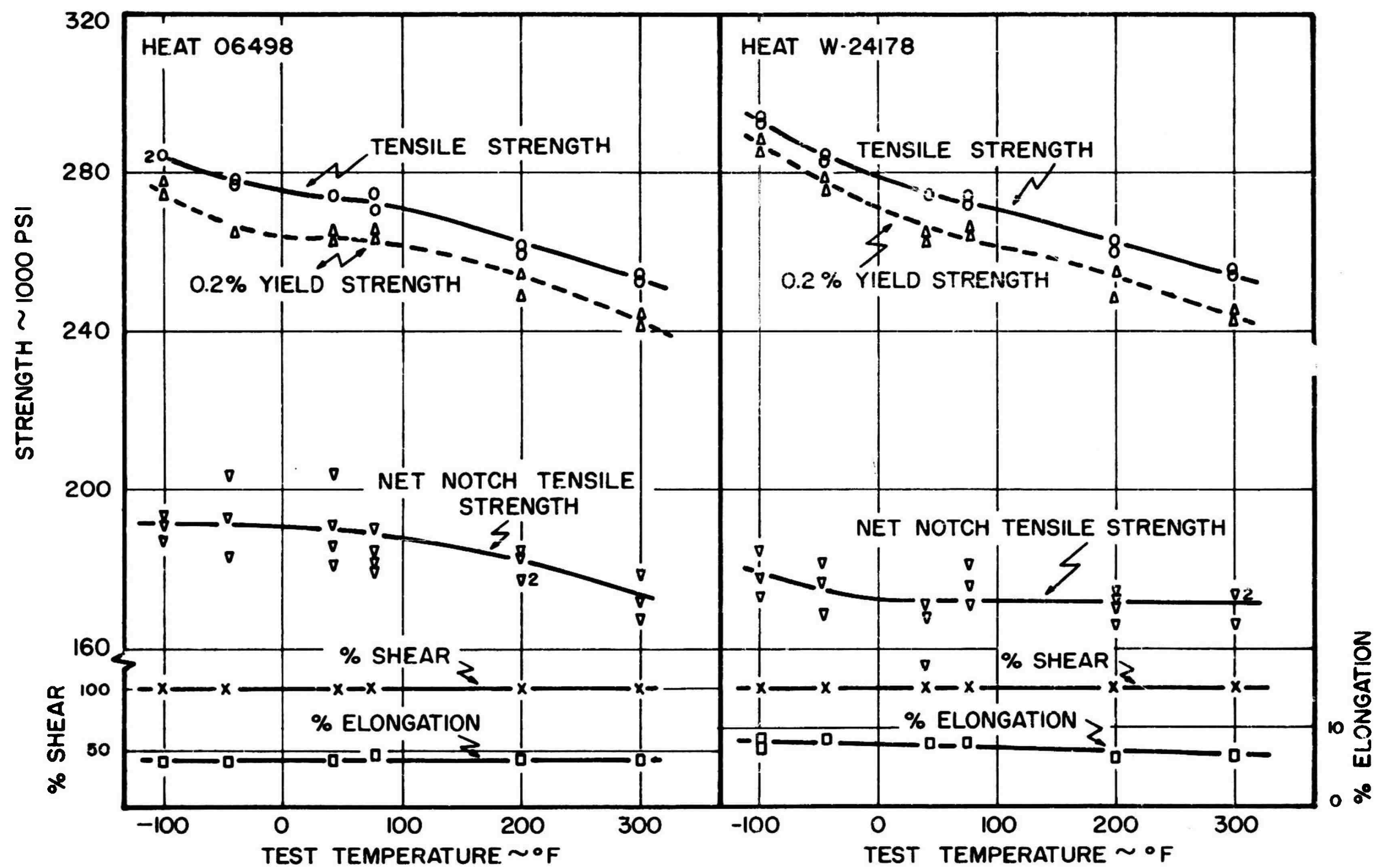

FIG. 37: INFLUENCE OF TEMPERATURE ON TENSILE PROPERTIES OF 18-5-9 MARAGING STEEL SHEET, LONGITUDINAL DIRECTION.

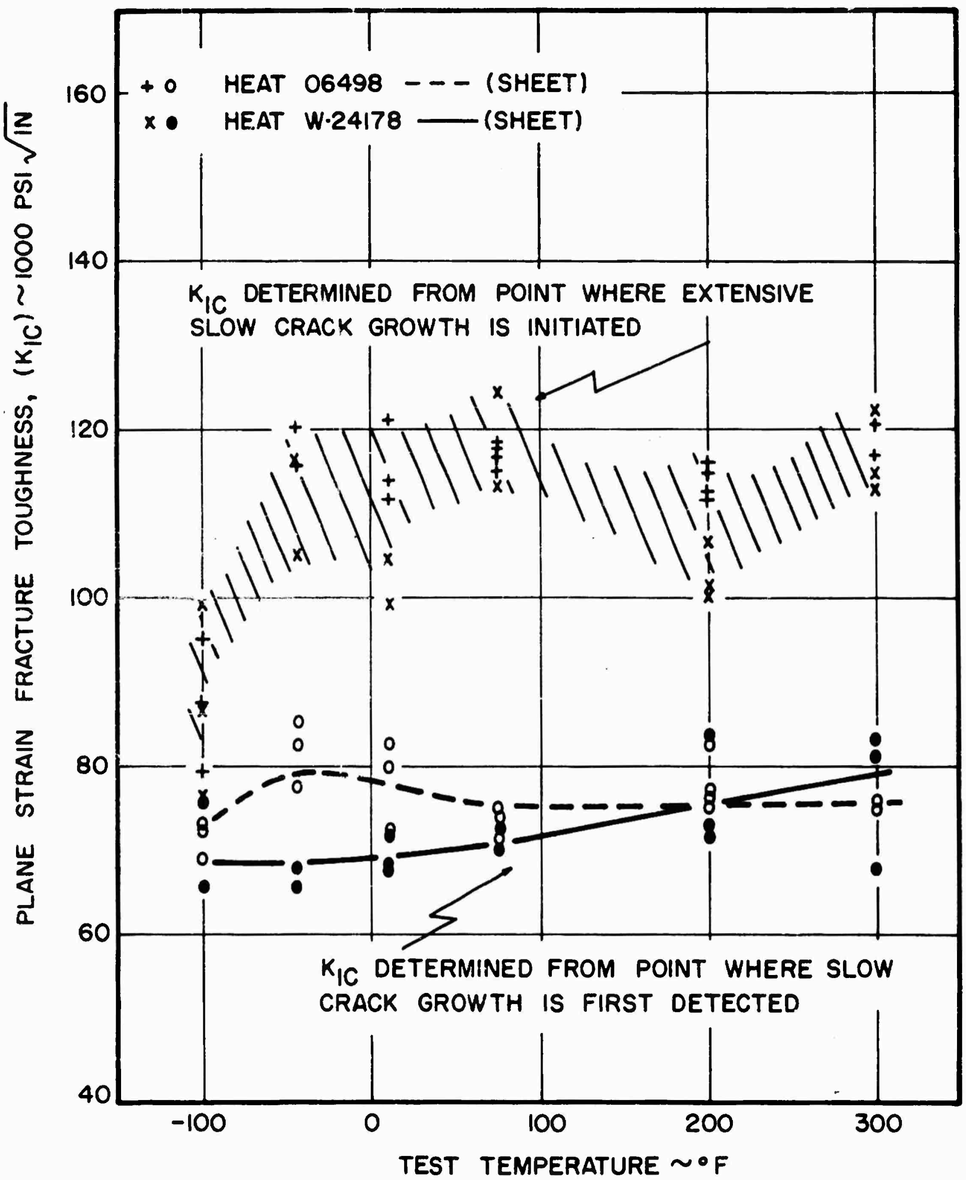

FIG. 38: INFLUENCE OF TEST TEMPERATURE ON PLAIN STRAIN FRACTURE TOUGHNESS, K_{IC}, OF 18-5-9 MARAGING STEEL SHEET, LONGITUDINAL DIRECTION.

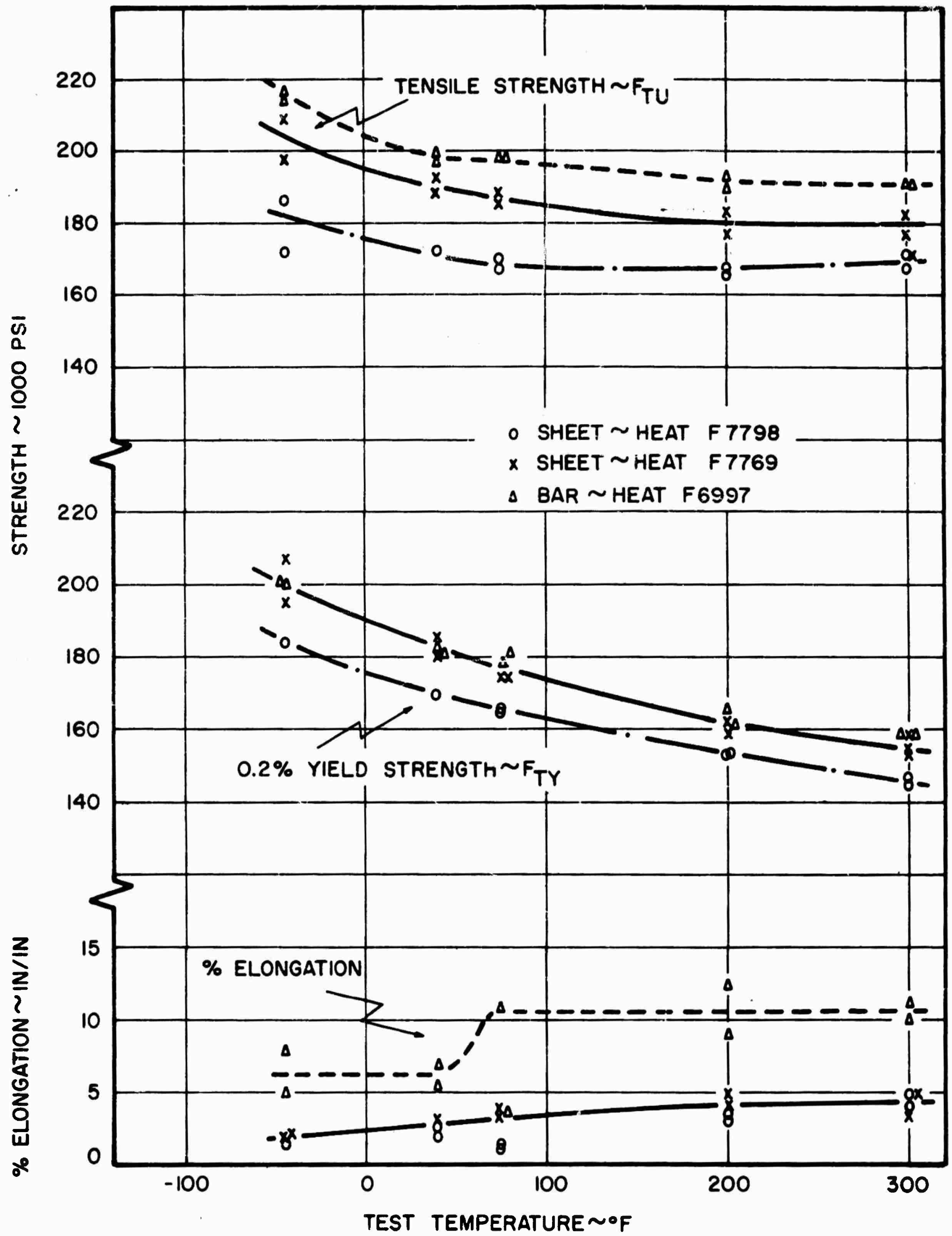

FIG. 39: INFLUENCE OF TEMPERATURE ON SMOOTH TENSILE PROPERTIES OF B120VCA TITANIUM, AGED AT 900°F FOR 72 HOURS IN VACUUM, LONGITUDINAL DIRECTION.

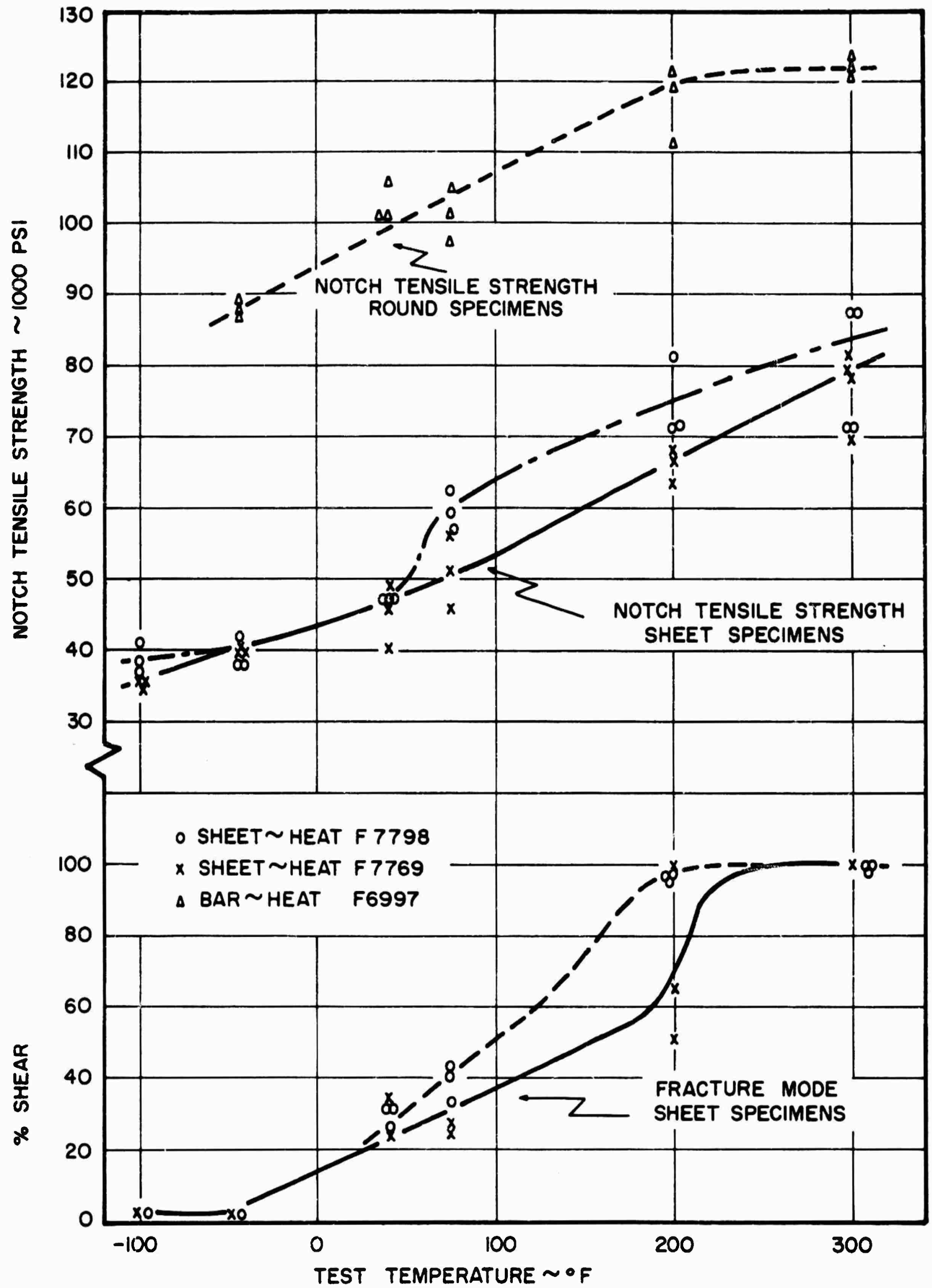

FIG. 40: INFLUENCE OF TEMPERATURE ON NOTCH TENSILE PROPERTIES OF B 120 VCA TITANIUM, AGED AT 900°F FOR 72 HOURS IN VACUUM, LONGITUDINAL DIRECTION.

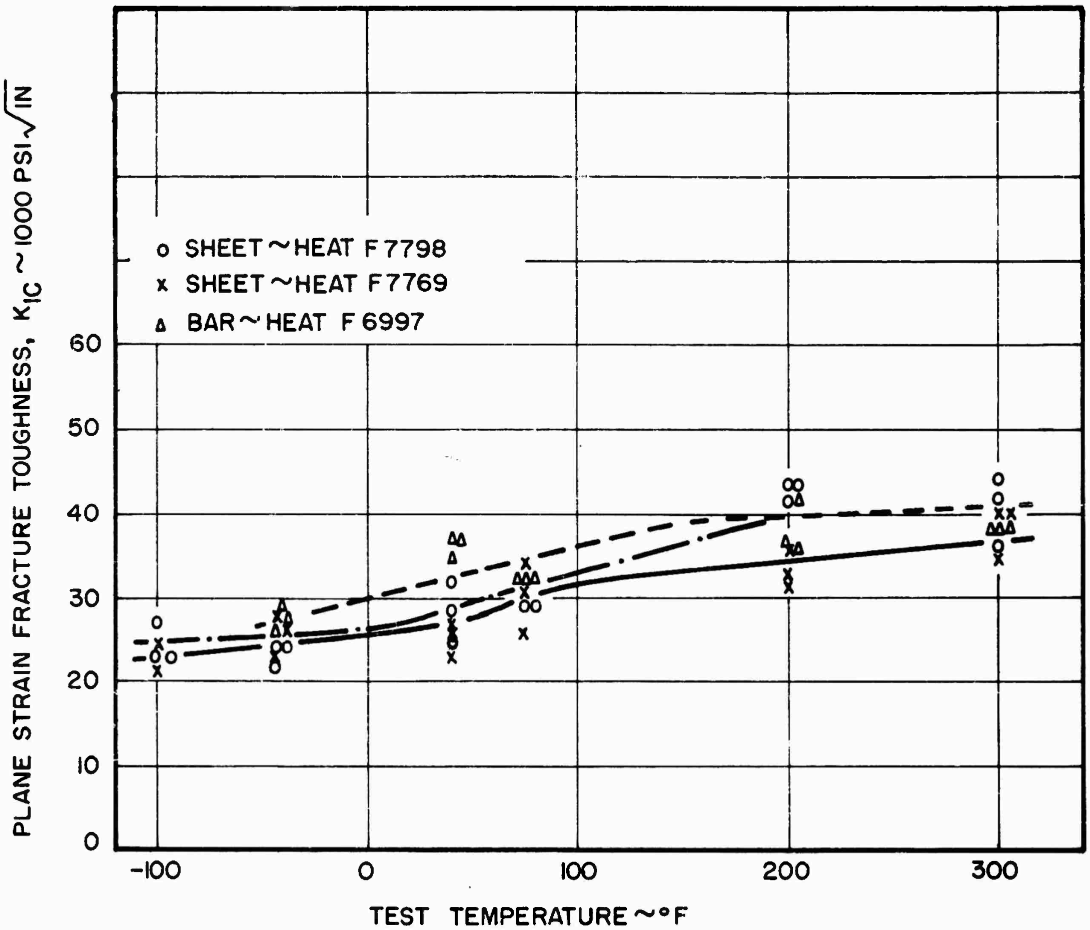

FIG. 41: INFLUENCE OF TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF B120VCA TITANIUM, AGED AT 900°F IN VACUUM, LONGITUDINAL DIRECTION.

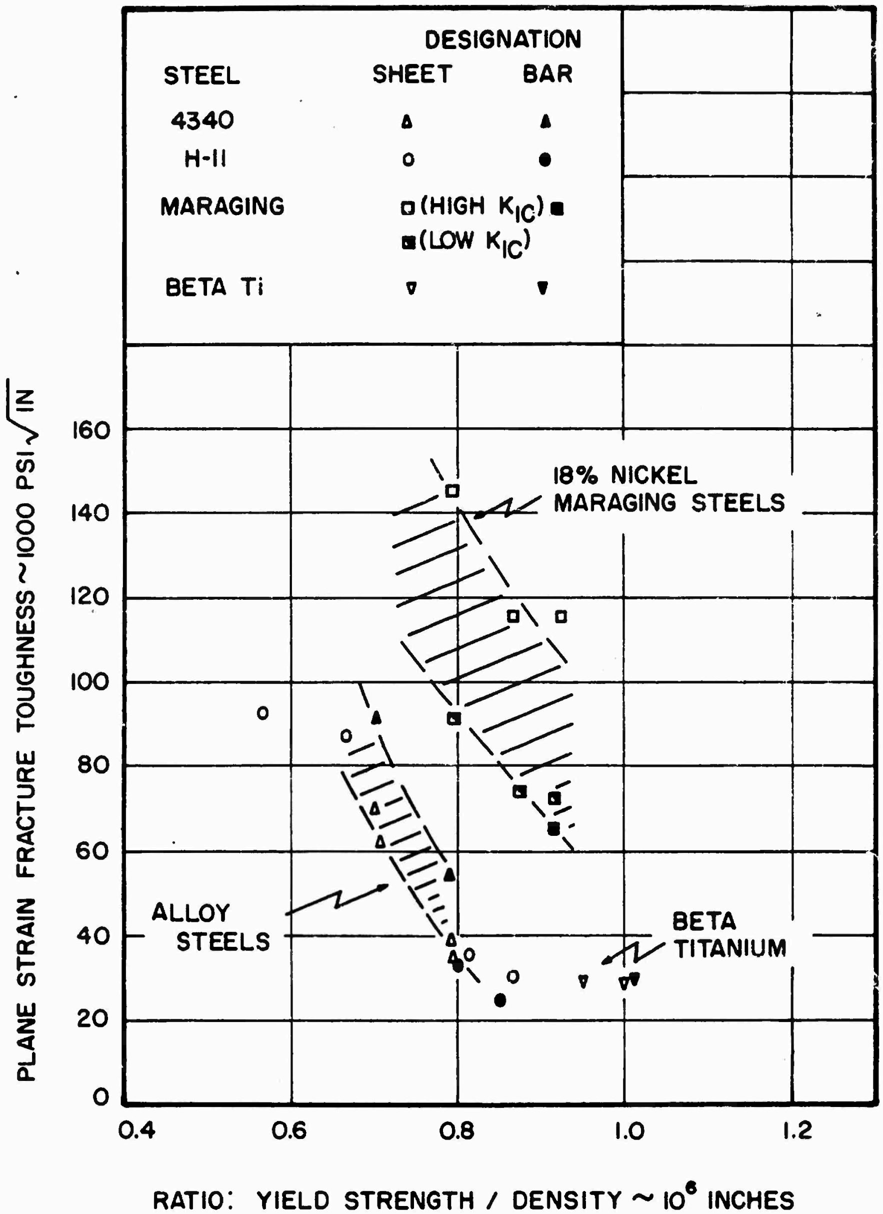

FIG. 42: COMPARISON OF PLANE STRAIN FRACTURE TOUGHNESS OF VARIOUS HIGH-STRENGTH MATERIALS AT ROOM TEMPERATURE.

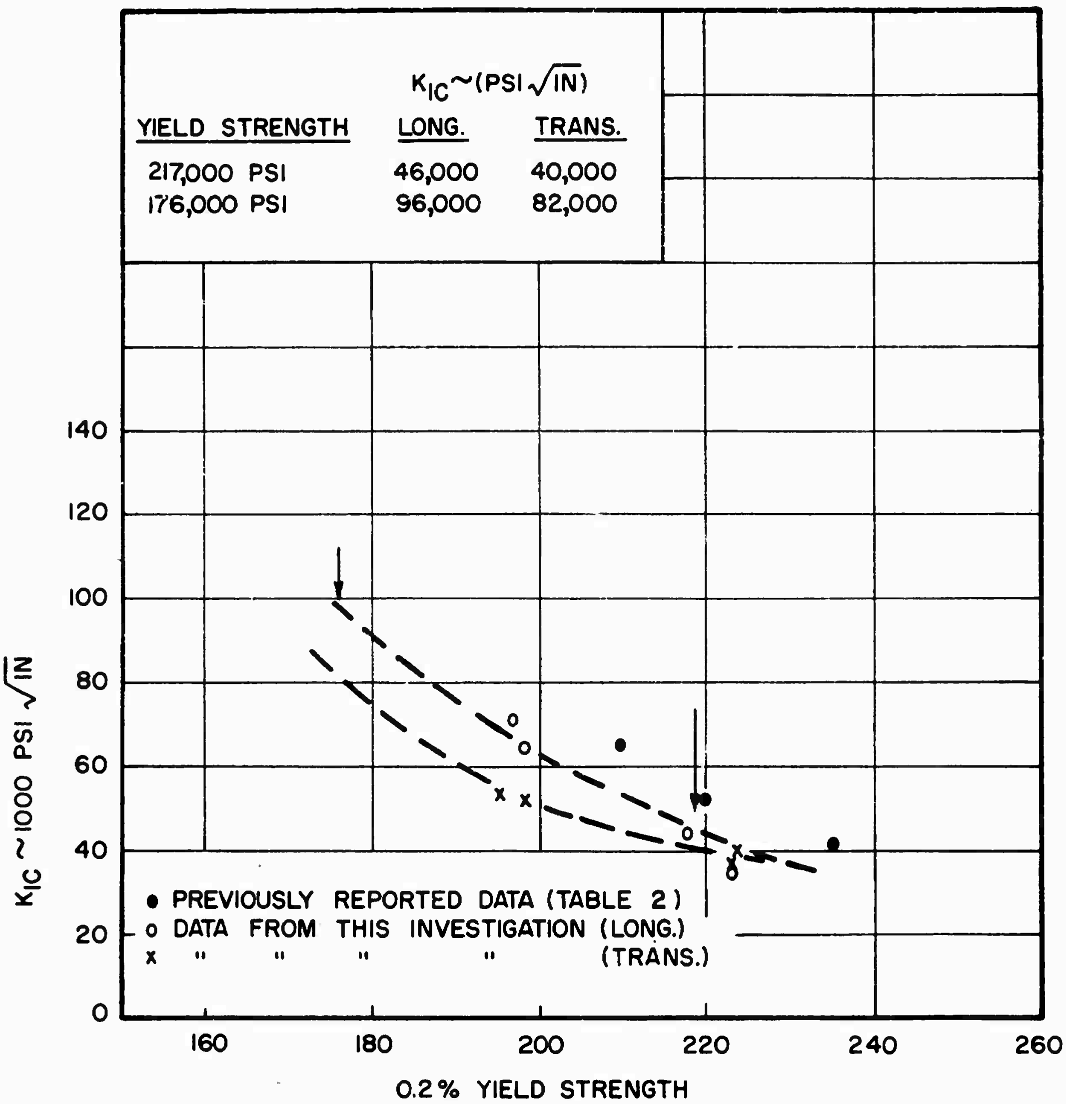

FIG. 43: K_{IC} DATA SELECTED FOR PRESENTATION AS TYPICAL ROOM TEMPERATURE SHEET PROPERTIES FOR ALLOY STEELS.

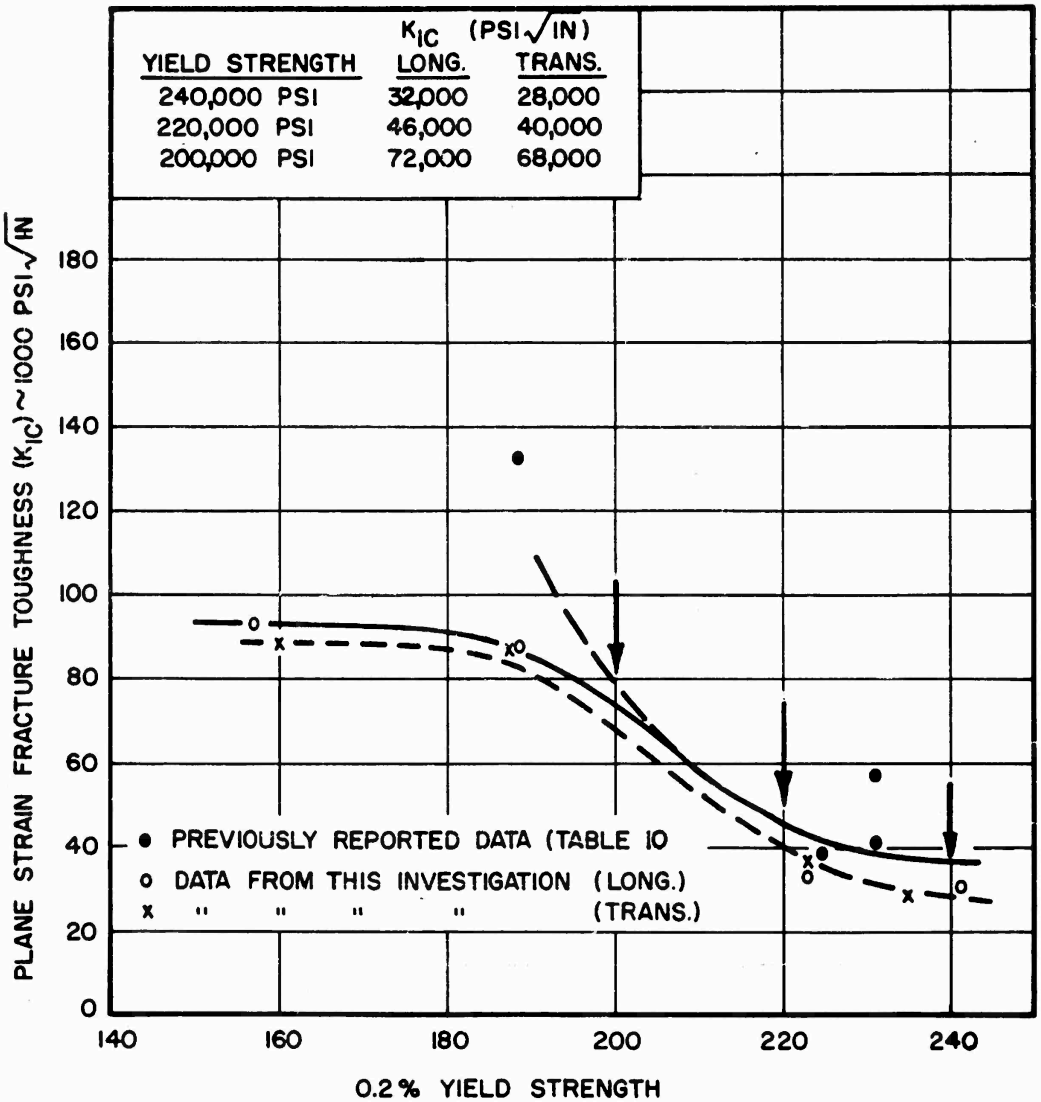

FIG. 44: K_{IC} DATA SELECTED FOR PRESENTATION AS TYPICAL ROOM TEMPERATURE SHEET PROPERTIES FOR 5Cr-Mo-V AIRCRAFT STEEL.

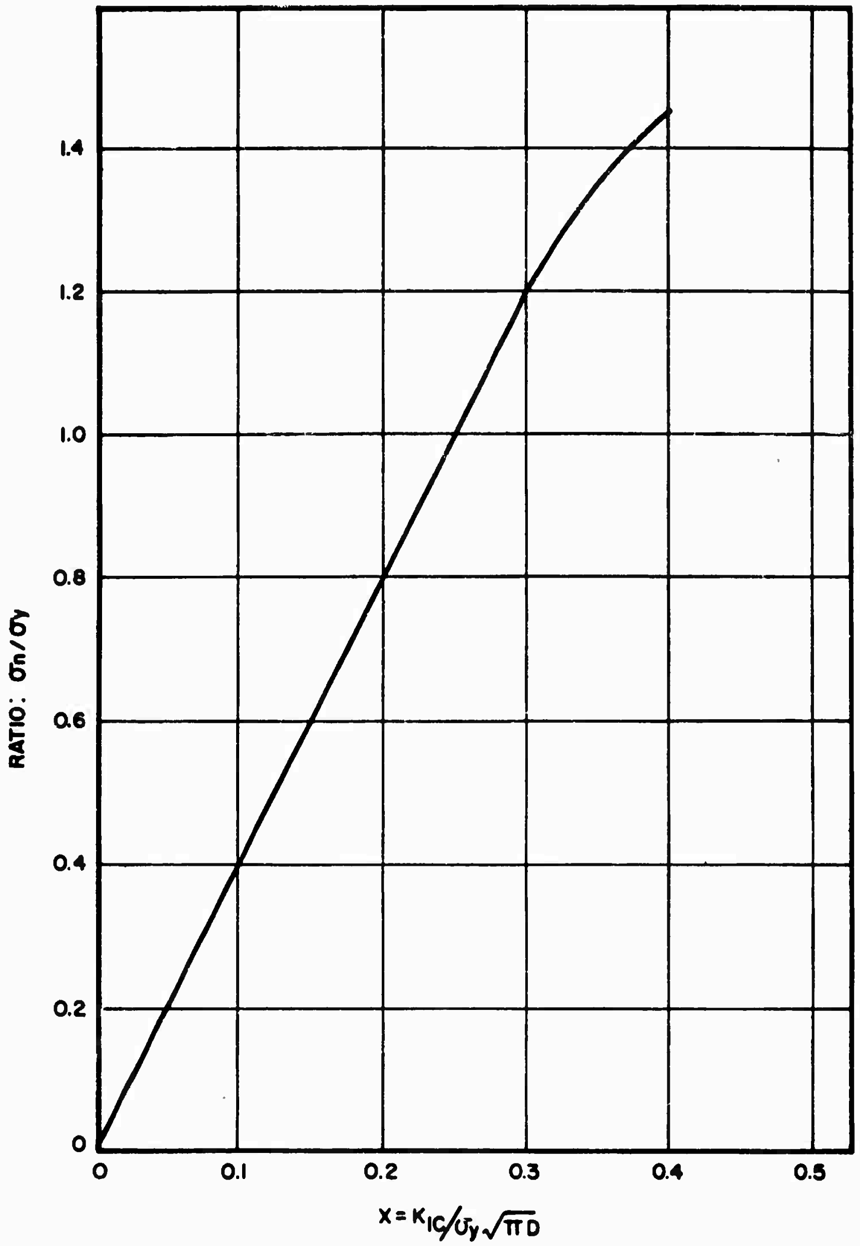

FIG. 45: GRAPHICAL METHOD FOR DETERMINING K_{IC}.

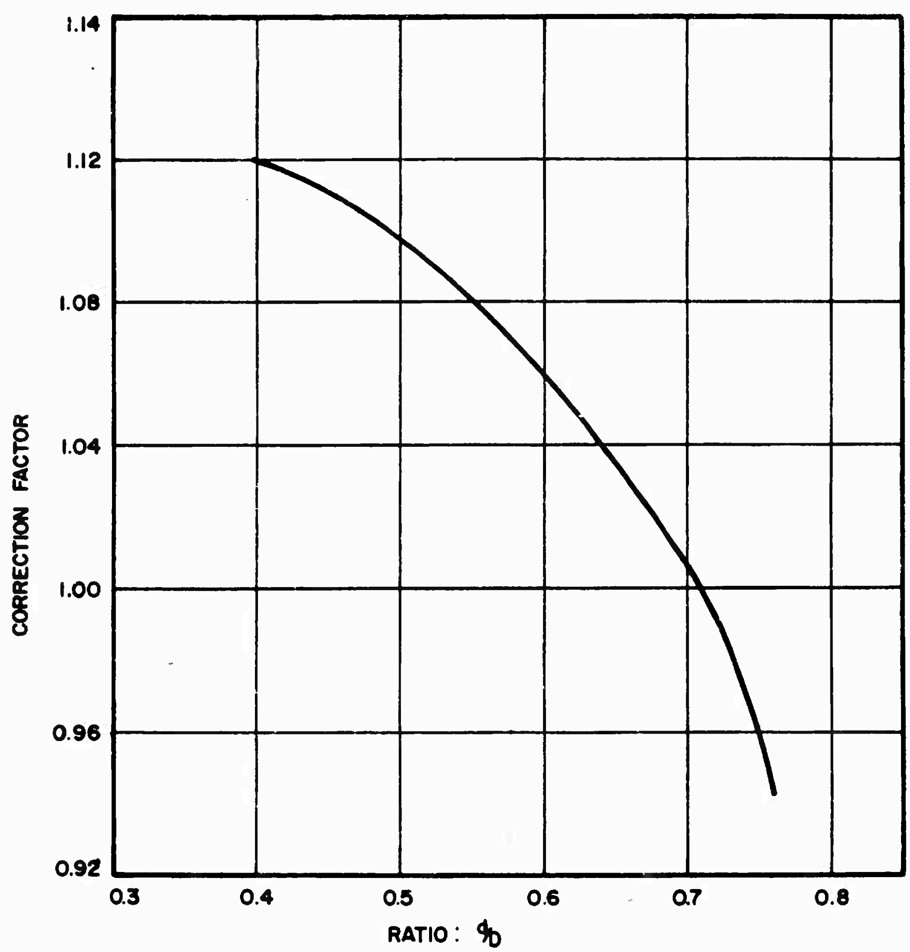

FIG. 46: CORRECTION FACTOR EMPLOYED FOR DETERMINING K_{IC} FROM SPECIMENS WITH VARYING d/D RATIOS.

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